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Operational energy capability portfolio analysis for protection of maritime forces against small boat swarms

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THESIS

OPERATIONAL ENERGY CAPABILITY PORTFOLIO ANALYSIS FOR PROTECTION OF MARITIME FORCES AGAINST SMALL BOAT SWARMS

by

Whye Kin Melvin Cheang

September 2016

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In this research, the Iranian training attack on a mock U.S. aircraft carrier in the Strait of Hormuz in February 2015 is the basis for the modeled scenario. A notional U.S. carrier group forms the baseline capability. An agent-based simulation scenario models the effectiveness of various capability options added to the baseline. These options include maturing developments such as the littoral combat ship (LCS) with modified Hellfire missiles, Spike LR missiles adapted onto autonomous 11-m unmanned surface vessels (USV), and advanced precision kill weapon system II missiles carried by Fire Scout tactical unmanned aerial vehicles (TUAV). A nearly orthogonal and balanced design, with 512 design points, yields broad insights and ensures an efficient experiment. Partition tree analysis, a non-parametric regression technique, identifies the presence and strength of influential factors. Efficient mixes of LCS, USVs, or TUAVs prove to be critical elements of protecting the maritime force while preserving its capabilities to accomplish the overall mission.

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OPERATIONAL ENERGY CAPABILITY PORTFOLIO ANALYSIS FOR PROTECTION OF MARITIME FORCES AGAINST SMALL BOAT SWARMS

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LIST OF ACRONYMS AND ABBREVIATIONS

AIS	automatic identification system
AOR	oiler
APKWS	advanced precision kill weapon system II
ASCM	anti-ship cruise missile
BCOT	Building Blocks to Composite Options Tool
C3	command, control, and communications
CBP	capability-based planning
CG	guided missile cruiser
CIWS	close-in weapon system
COI	critical operational issue
CVN	nuclear-powered aircraft carrier
DDG	guided missile destroyer
DOE	design of experiment
ESSM	evolved sea sparrow missile
IRGCN	Iranian Revolutionary Guard Corps Navy
LCS	littoral combat ship
LR	long range
M&S	modeling and simulation
MANA	Map Aware Non-Uniform Automata
MBSE	Model Based Systems Engineering
MLRS	multiple launch rocket system
MOE	measure of effectiveness
MOP	measure of performance
NATO	North Atlantic Treaty Organization
NOB	nearly orthogonal and balanced
NOLH	nearly orthogonal Latin hypercube
ODASD(OE)	U.S. Office of the Deputy Assistant Secretary of Defense for Energy, Installations, and Environment
ONI	U.S. Office of Naval Intelligence
ONR	U.S. Office of Naval Research

OPV	offshore patrol vessel
Orbat	order of battle
PEF	Pareto efficient frontier
R&D	research and development
RAM	rolling airframe missile
RPG	rocket-propelled grenade
SAM	surface-to-air missile
SE	systems engineering
SM	standard missile
SSMM	surface-to-surface missile module
TUAV	tactical unmanned aerial vehicle
UCAV	unmanned combat aerial vehicle
USV	unmanned surface vessel

EXECUTIVE SUMMARY

This research provides insights to decision makers on selecting an operational energy-efficient and cost-effective capability portfolio for the protection of a maritime force against a conventional small boat swarm attack. It examines the trade space between weapon consumption, fuel consumption, and cost, as well as identifies effective and feasible operational energy options to be part of the capability portfolio against small boat swarms.

A small boat swarm is a cheaper, asymmetric threat that can deplete a naval force's resources and create risk to overall mission accomplishment. This threat is asymmetric in terms of its numbers, agility and nimbleness. The U.S. Navy needs an operational energy capability portfolio analysis to ensure that it can achieve its conventional warfare missions. Such a portfolio should concurrently be cost-effective to ensure good use of finite defense dollars and not overspend on defense against the small boat swarm threat. These issues give rise to the main research question: How can we select an energy-efficient and cost-effective capability portfolio to defend against, and reduce disruption to conventional missions facing, an unanticipated asymmetric threat's attack?

The IRGCN 2015 training attack on a mock U.S. Navy aircraft carrier in the Strait of Hormuz during February 2015 inspires the operational scenario. The adversary comprises a notional swarm of IRGCN small boats carrying anti-ship cruise missiles (ASCM) and adopting a multi-axis surprise attack. This thesis analyzes existing and maturing capability portfolio options to defend against the swarm attacks. The baseline capability is a typical carrier group comprising one aircraft carrier, one cruiser, two destroyers and one oiler assumed transiting to the Persian Gulf for a conventional mission. Limiting the notional maturing capability options to those reaching maturity for equipping within the next 10 to 15 years makes these options useful in informing decision makers today. The notional options include the littoral combat ship (LCS) with modified Hellfire missiles, 11-m autonomous unmanned surface vehicles (USV) armed with Spike long-range (LR) missiles, and Fire Scout tactical unmanned aerial vehicles (TUAV)

armed with the Advanced Precision Kill Weapon System II (APKWS) missiles. We explore different mixes of these capabilities as augmentation to the baseline capability.

As a key instrument in the systems engineering approach to study capability requirements, computer experimentation is a powerful and proven method. It is increasingly the primary choice for exploring the decision space of complex problems; in particular, the trade space in a capability portfolio. Experimentation enables analysts to obtain insights by testing different variables, such as force configuration and weapon use policy, with regard to certain performance measures. Such insights identify required capabilities that meet mission objectives. The scenario is instantiated using Map Aware Non-Uniform Automata (MANA), an agent-based simulation software platform. Figure 1 shows a snapshot of a simulation run in MANA with enemy units in yellow and friendly units in blue.

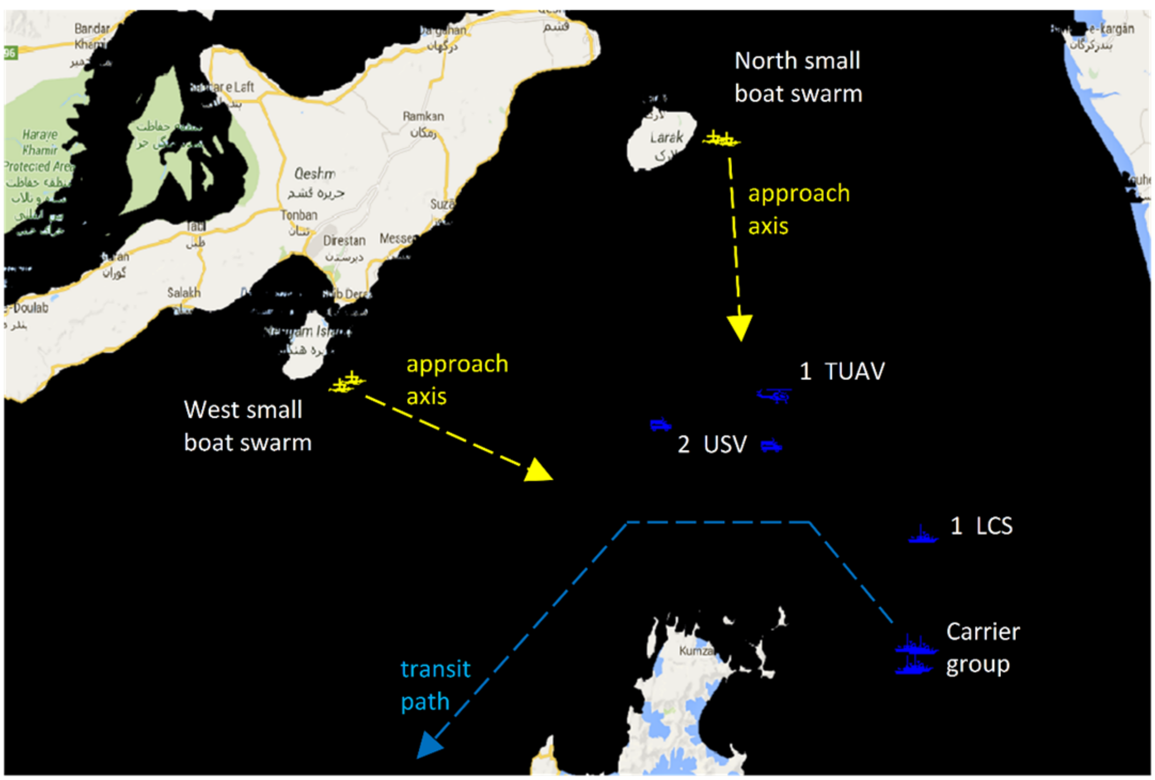

Figure 1. Snapshot of a Simulation Run in MANA (Enemy Units in Yellow; Friendly Units in Blue).

We used a design of experiment (DOE) approach to study key input factors, vary such factors systematically, and seek the most insights from the simulation efficiently. Controllable factors include the numbers of platforms and the use of surface-to-air missiles. Uncontrollable factors cover weapon hit probabilities and sensor ranges for both forces, as well as the number of enemy boats. We use the partition tree tool in JMP, a statistical discovery software from SAS, for the data analysis. We analyze the modeling results, broadly, in terms of force protection effectiveness, weapon and fuel consumption, and financial costs.

In answering the research question, the results provide useful insights into the influential factors, as well as energy- and cost-efficient configurations involving the maturing capabilities.

The number of LCSs, as part of a reconnaissance force ahead of the carrier group, is most influential in reducing the mean missile leakers, the mean boat leakers, the mean use of friendly surface-to-air missiles (SAM), and the mean cost of overall weapons expended. This is likely due to the number and range of the modified Hellfire missiles the LCS carries, as compared to the Spike LR and APKWS weapons. The LCS also enables armed TUAV operations by carrying and deploying the TUAVs. In turn, adding LCSs increases the mean fuel consumed and the mean cost of added force.

Arming the TUAVs with the APKWS has a partial influence on reducing the use of SAMs, Hellfire missiles, Spike missiles, and the overall cost of weapons expended. This is mainly due to the APKWS being the cheapest missile used against the enemy boats. The number of TUAVs has similar effects, but to a lesser extent.

The number of USVs is generally not influential in improving mission performance. This is likely due to the small number and short range of the Spike missiles the USV carries.

This thesis identifies a minimum configuration for the reconnaissance force, specifically having at least three LCSs and five to six armed TUAVs, to attain zero and close to zero (≤ 0.5) missile and boat leakers, assuming the LCSs carry and deploy the armed TUAVs. Such a configuration resulted from the LCS and armed TUAV being

more influential on reducing leakers, as compared to the USV equipped with Spike missiles. This minimum configuration ensures that the naval force could continue unharmed on its conventional mission.

Imposing upper limits, from an efficiency perspective, on the reconnaissance force's diesel and aviation fuel consumption, as well as costs of weapons expended and added force, reduces the maximum number of LCSs and TUAVs that can be deployed.

Mitigating policies, including operational and doctrinal ones, to defend successfully against conventional attacks from a small boat swarm involve selecting a "right-sized" mix of LCSs and armed TUAVs, that can provide effective force protection and, at the same time, limit fuel consumption, cost of weapons expended, and cost of added force.

Notional near term R&D options of increasing LCS Hellfire missile capacity, USV Spike missile capacity, TUAV APKWS missile capacity, and Spike missile range are not influential in improving mission performance. Scaling autonomous USV technology to deploy up to 24 USVs from the current five has a moderate influence on reducing missile leakers. Compared with the R&D options, the number of LCSs and arming the TUAVs appear to be better investments if greater performance is desired.

The uncontrollable factors have minimal impact on missile and boat leakers, fuel and weapon consumption, and costs. The capability options perform relatively robustly across a slew of different weapon hit probabilities, sensor range performances, and enemy boat numbers.

Three LCSs with five to six armed TUAVs is a preliminary optimal force configuration, assuming the LCSs carry and deploy the TUAVs.

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I. INTRODUCTION

A. PURPOSE

This research provides decision makers with insights gleaned from examining the trade space between weapons expended, fuel consumption, and cost in protecting a maritime force against a conventional small boat swarm attack.

B. PROBLEM STATEMENT

A small boat swarm is a large number of inexpensive, agile, and armed boats that pose an asymmetric threat to the U.S. Navy's conventional warfare missions. This threat is asymmetric in terms of its numbers, agility and nimbleness. The swarm boat threat has been extensively studied in literature such as IHS (2014b), ONI (2009, 23) and Haghshenass (2006). Due to their large numbers, these boats can saturate and penetrate a more expensive and advanced task group's defenses. The small boat swarm attacks deplete the force's resources and create risk to overall mission accomplishment. A recent demonstration of this asymmetric threat is the Iranian Revolutionary Guard Corps Navy (IRGCN) attack on a mock U.S. aircraft carrier with tens of speedboats during a major training exercise in the Strait of Hormuz (IHS 2015c; *New York Times* 2015). Various literature, such as ONI (2009) and Haghshenass (2006; 2008), describe IRGCN's strategy of small boat swarm attacks. A likely extension of the swarm boat attack is China's potential use of stealthy Type 022 catamarans with long-range anti-ship cruise missiles (ASCM), a potential scenario described by Navarro (2016).

Within the systems engineering (SE) process, requirements development is a critical step for ensuring that stakeholder needs are met. It remains true in the study of this capability package. An operational energy (defined in ODASD(OE) 2016) capability portfolio is needed to ensure operational reach (defined in Mullen 2011, GL-15) in the U.S. Navy's conventional warfare missions. Such a portfolio should concurrently be cost-effective to ensure good use of finite defense dollars and not overspend on defense against the asymmetric threat. For instance, the U.S. Navy is experimenting with robotic boat swarms to counter the small boat swarm attacks (Hsu 2014; IHS 2014a)—but how

sustainable is this robotic swarm in terms of operational energy? Does it make economic sense to spend much more on defense against a less expensive threat than to unlock resources for other critical military capabilities? Effective force protection must still be maintained if more energy-efficient and less costly capability portfolio options are desired. These issues lead to the main research question: How can we select an energy-efficient and cost-effective capability portfolio to defend against, and reduce disruption to conventional missions facing, an unanticipated asymmetric threat's attack?

C. SURVEY OF RECENT STUDIES

A survey of extensive studies on countering small boat attacks from different perspectives provides the academic context to this research's focus on the knowledge gap of countering conventional small boat swarm attacks.

Sirrs (2002) examines the application of better operational planning that included the employment and sequencing of operational tasks, such as the use of air superiority, surveillance, and operational fires, to counter small boat attacks with Iranian coastal waters as one scenario. Martinez Tiburcio (2005) and Singh (2010) studies capability factors that were important in enhancing coastal defense for the Campeche Sound and Israeli coast, respectively.

On better modeling and simulation techniques, Harney (2003) develops a Java-based application that can model "what-if" threat scenarios in higher fidelity. Ng (2007) develops the modeling of dynamic threat behaviors. Sullivan (2006) builds on Harney's work by expanding the fidelity of the simulation model in force protection scenarios. Wong (2010) employs agent-based simulation to study the impact of different defender tactics versus different attacker tactics in a port security setting.

Force protection of ships was another key area. Tiwari (2008) studies training and small caliber weapons (25 mm and below) gaps and enhancements in protecting a destroyer (DDG) against terrorist small boat attacks. Abel (2009) finds that having a mix of system-directed weapons, as opposed to the existing manually aimed weapons, on a frigate significantly enhances survival in counter-piracy patrol missions. McKeown (2012) employs agent-based simulation in studying Offshore Patrol Vessel (OPV)

effectiveness against small boat attackers that use suicide weapons. Kaymal (2013) researches the effectiveness of protecting a convoy against explosive-laden terrorist boats.

On exploiting net-centric maritime warfare, Marland, Galligan, and Galdorisi (2005) use agent-based simulation to examine the impact of four different capability levels of shared situation awareness (from none to having inorganic targeting) on defending against three different categories of small boat attackers—from rocket-propelled grenades (RPG) to ASCMs. They find that against the small boat attackers with ASCMs, it is useful to employ helicopters or unmanned combat aerial vehicles (UCAV) at far-enough ranges to reduce the threat to friendly ships. The fundamental gain is early attrition and maximizing ships' weapon ranges.

The knowledge gap observed across these studies is the analysis of an energy-efficient and cost-effective capability portfolio in countering small boat swarm attacks utilizing ASCMs. Previous studies focus solely on force protection effectiveness. This thesis addresses this gap.

D. SMALL BOAT DEFINITION

It is necessary to define the class of small boats being studied, as there are multiple definitions and small boat classes. Marland, Galligan, and Galdorisi (2005) coin a useful categorization that is referred to in this research. The categories are, in a broad sense, "type 1 RPG/suicide bombs (3-500 m)," "type 2 multiple launch rocket system (MLRS) rocket (8 km)," and "type 3–missile/torpedo." This research focuses on the IRGCN small boats with ASCMs, which belong to the "type 3" category. The survey of recent studies showed that countering "type 1" and "type 2" attacks has been studied.

E. CRITICAL OPERATIONAL ISSUES

The critical operational issues (COI) for the capabilities facing the conventional small boat swarm attack focus on the key gaps in a system (Stevens 1986, 19). Addressing the COIs requires an operational context. In this thesis, a carrier group is to conduct a primary mission of attaining air superiority and requires movement from the

Indian Ocean to the Persian Gulf. The carrier group encounters a surprise conventional small boat swarm attack during transit in the Strait of Hormuz. The friendly force commander would be concerned about the ability to carry on with the primary mission and would want to ensure force survivability from the small boat attack as well as conserve weapons and fuel against the swarm attack. These two considerations affect the ability to accomplish the primary mission. However, it is not efficient to use costly defense capabilities against the cheaper small boat swam threat. Cost-efficient options should be examined. For this study, the identified COIs are:

1. How well can the friendly force survive the small boat swarm battle?
2. How much of the maritime force's weapons and fuel is used in the small boat battle, with a view to weapon and fuel sufficiency for the primary mission post swarm attack?
3. How costly is the defense capability option?

F. RESEARCH QUESTIONS

While the COIs provide clarity on the key issues, research questions drive clarity on addressing the issues. The main research question is reiterated:

- How can we select an energy-efficient and cost-effective capability portfolio to defend against, and reduce disruption to conventional missions facing, an unanticipated asymmetric threat's attack?

The secondary research questions, which can be categorized under force protection, weapon and fuel consumption, and cost, are:

1. Force protection — How effective is the force protection of the naval force so that the naval force can continue on its primary mission?
2. Weapon and fuel consumption — How do operational energy considerations constrain the options of a naval force that is defending against a combatant's swarm of small boats?
3. Weapon and fuel consumption — What mitigating policies (operational and doctrinal) can be applied to defend successfully against a swarm of small boats in a maritime war scenario?

4. Cost — What are cost-effective options for a maritime unit to defend successfully against a combatant’s swarm of small boats?

G. BENEFITS OF STUDY

The research provides insights to decision makers on selecting an operationally effective, cost-effective, and operational energy-efficient capability portfolio for the protection of a maritime force against a conventional small boat swarm attack. This study recommends feasible operational energy options to be part of the capability portfolio against small boat swarms.

The capability-based planning (CBP) process (National Research Council, Committee on Naval Analytical Capabilities and Improving Capabilities-Based Planning, and U.S. Navy 2005) aptly describes the value of this research. The process is defined as “planning, under uncertainty, to provide capabilities suitable for a wide range of modern-day challenges and circumstances while working within an economic framework that necessitates choice” (21). Capability-based planning aims to “provide more meaningful information and to better inform strategic-level decision making” (28) and “identify and analyze key risks so as to inform leadership decisions on resource allocation” (28). Part of the CBP process “must include ‘smart,’ low-resolution modeling and analysis (grounded in higher-resolution work or empirical data when appropriate) that puts a premium on higher-level insights rather than focusing on minutia” (7).

H. SCOPE OF STUDY

This study is a capability engineering effort that provides an analysis of options for a capability portfolio. This effort fits in the first two stages of the SE functions (see Figure 1), as presented by Hernandez (2015) in a SE3250 course lecture, as well as in the operational need and requirements analysis portions of the Department of Defense’s SE process (see Figure 2). Computer experimentation, a key instrument in the capability engineering effort, provides a method to explore possible tradeoffs, as well as acts as a means to generate data for the comparison of performance measures.

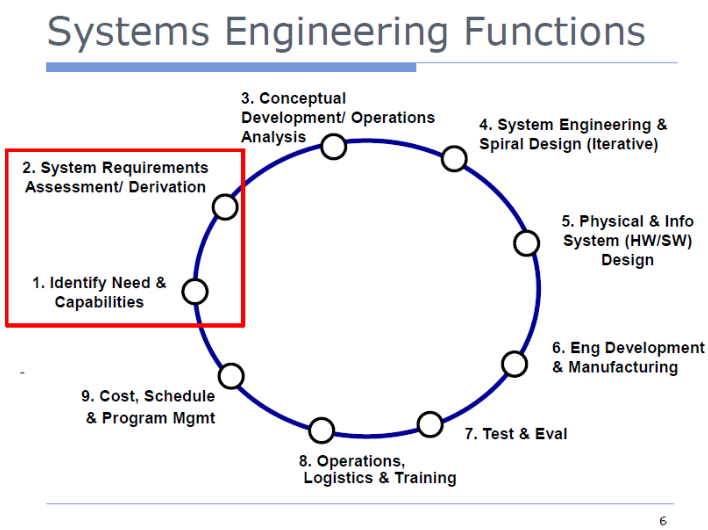

Figure 1. Systems Engineering Functions. Source: Hernandez (2015).

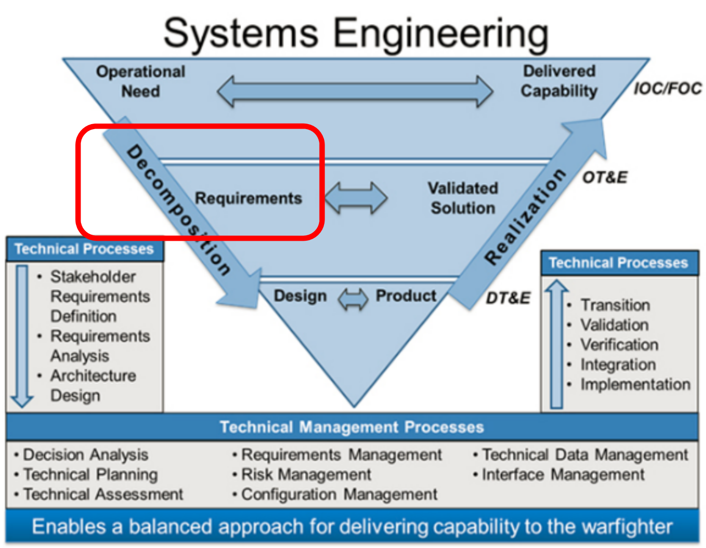

Figure 2. Department of Defense's Systems Engineering Process. Adapted from Defense Acquisition University (2016).

This study proposes an operational energy-based examination of important factors that impact a capability portfolio against the small boat swarm threat at the task-group level. A task group typically comprises one aircraft carrier, one cruiser, two destroyers and one oiler (U.S. Navy 2016). Existing and maturing capability portfolio options to defend against the swarm attacks are analyzed. The modeled scenario is inspired by the IRGCN's training attack on the mock carrier.

The screening methodology from Davis et al. (2008) is adapted to develop and screen different capability options. The proposed capability portfolio options studied are limited to capabilities reaching maturity within the next 10 to 15 years. Open source data such as Jane's information on capabilities is used—actual confidential data could be used in a follow-on study to produce results that are more accurate. A design of experiment (DOE) approach is used to generate data efficiently that can yield broad insights from investigating the experimental space. The impact of different factors on the measures of effectiveness (MOE) is analyzed using the partition tree statistical analysis tool. The impact of factors on the different MOEs is tabulated for useful comparison. This study is unclassified and not based on interviews, surveys, or questionnaires.

The scope of this research includes missile combat exchanges involving enemy ASCMs, friendly surface-to-air missiles (SAM), and missiles used against enemy boats, such as the Hellfire, Spike LR, and Advanced Precision Kill Weapon System II (APKWS) missiles. Gun combat exchanges have been covered in previous studies (Abel 2008; McKeown 2012; Kaymal 2013). Enemy missile and boat leakers will be the metrics for force protection effectiveness instead of combat survivability of the carrier group. The latter is highly complex and involves considerations such as missile defense, gun defense, electronic warfare, and ship design.

I. THESIS ORGANIZATION

Chapter II is the in-depth review of related studies that forms the academic context and identifies the knowledge gap. Chapter III articulates the development of the simulation model, including the operational scenario used in the model. Part of the Model Based Systems Engineering (MBSE) process is adopted where a simulation model is built and used to provide a systematic analysis of the impact of factors on capability requirements. The Map Aware Non-Uniform Automata (MANA) simulation software was used to study the effectiveness of different capability portfolio options. Chapter IV contains the MOEs, DOE, and the analysis of experiment results. The different capability portfolio options are analyzed and compared using the MOEs as the basis. Chapter V summarizes the insights and recommendations.

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II. ACADEMIC CONTEXT AND KNOWLEDGE GAP

A. INTRODUCTION

Reviewing literature on countering small boat attacks provides the academic context for the knowledge gap this research addresses. While academics have studied multiple aspects on countering small boat attacks, there is still a dearth of knowledge on countering conventional small boat attacks made on a maritime force. Sirrs (2002) advocates the application of air superiority, effective surveillance, and operational fires to reduce the lethality of the small boat threat prior to inserting a carrier group. Better modeling of small boats attack behavior and combat scenarios provided a greater fidelity of knowledge in informing capability, doctrine and training. Studies on port security, coastal defense, high-value unit escort, and single ship defenses help inform gaps in capabilities and doctrine. Most of these studies, however, were found to focus on non-conventional attacks at close ranges, for instance, less than 5000 m. Research studies show these attackers typically employ suicide bombs, short-range handheld weapons, or both. One common thread observed across the studies is the recognition that small boat attacks continue to be a significant asymmetric challenge to friendly forces and infrastructure. Another theme is that these studies focus on countering terrorist small boat attacks utilizing suicide weapons, human-held ranged weapons, or a mix of both.

B. BETTER OPERATION PLANS

Sirrs (2002) studies operational plans to counter small boat attacks, potentially from Iran and North Korea in their coastal waters against U.S. forces. Such attacks are part of what he terms a “timeless asymmetric strategy for those smaller navies who are willing to confront opponents possessing overwhelming naval and maritime power.” He draws insights from the 1945 invasion plan of southern Japan codenamed OLYMPIC. Sirrs identifies that the Strait of Hormuz has offshore islands that provide good battle preparation areas for small boat swarms and that the close proximity of the shipping lane in the narrow strait to these preparation areas enhances the opportunity for a surprise attack. He assesses that shipborne defense capabilities are not fully effective against

small boat attacks and proposes that proper coordination and ordering of operational tasks is needed to reduce or defeat the enemy small boats and coastal defenses. The U.S. forces should conduct certain operational tasks to reduce or even eliminate the small boat threat, prior to inserting the carrier battle group. This includes achieving control of the air space; neutralizing the enemy's means of command, control, and communications (C3); destroying the coastal defense batteries; achieving good surveillance on small boat operating areas; and destroying supporting infrastructure.

This thesis takes a different perspective from Sirrs by studying options for an operational energy-efficient and cost-effective force protection of a transiting carrier group that encounters a surprise small boat swarm attack. The impact of island groups and the narrowness of the Strait of Hormuz informs the operational scenario.

C. MODELING THREAT SCENARIOS AND BEHAVIORS

Improvements for modeling attack scenarios and behaviors of terrorist small boat attacks provide higher fidelity for capability and doctrine development. Harney (2003) assesses there was a gap in simulating "what-if" scenarios amid then-existing simulation tools typically used to train sailors or enhance situation awareness. Choosing the important warfare areas of Anti-Terrorism and Force Protection, Harney develops a "fully integrated, prototypical, Java-based application" that incorporated "various Open-Source, web-based technologies." His tactical-level simulation tool, with 2D and 3D visualization features, is geared at improving "the tactical awareness and defensive posture of ships defending against terrorist attacks in port," including in the areas of sailor training, doctrine development and tactics planning.

Ng (2007) assesses that modeling threat behaviors typically had "predefined or random paths and fixed responses." He suggests advancing the state of modeling by incorporating the changing behaviors found in asymmetric threats. His goal is to have a more realistic and higher-fidelity model of asymmetric threats to inform capability and doctrine development. Ng employs discrete-event simulation and a multi-agent system to model the complex and adaptive behaviors of the threats. In his enhanced modeling, Ng demonstrates that the threats can show more flexible behavior and greater ability to adapt

in situations. A wider spectrum of maritime threat scenarios can now be simulated. This, in turn, informs maritime force and coastal infrastructure development plans.

The two authors provide useful insights into modeling and simulation (M&S), particularly on the strengths of visualization in simulation tools and the impact of greater fidelity in modeling threat behavior.

D. ENHANCING PORT SECURITY AND COASTAL DEFENSE

Sullivan (2006) indicates that there was a gap in determining "the most effective combination of systems and employment for a wide range of possible terrorist attack scenarios" to inform capability procurement. He builds on Harney's work (2003) and expands the fidelity of modeling the threat, friendly forces and installations, and capability effectiveness in force protection scenarios. His work results in an M&S tool that is scalable and can be flexibly applied to different scenarios. The tool can carry out large-scale agent-based simulations, provide 3D visualizations, generate reports, and support statistical analysis.

Wong (2010) determines that small boat attacks continue to be a potential risk because the attackers could mask themselves among numerous innocuous small vessels that moved in close proximity to valuable shipping and coastal infrastructure. He studies the impact of various attacker and defender tactics on the effectiveness of intercepting attacking speedboats. The analysis uses results from a scenario built with the agent-based simulation tool MANA. His study finds that "defenders are highly susceptible to diversionary attacks regardless of tactics employed, but their effectiveness can be improved by retaining sufficient defensive assets in preparation for a potential follow on attack." Another insight gained was that "anticipating the heading of the attacker is a critical factor for a successful engagement."

Coastal defense against terrorist small boats, involving defense of nearby waters that lay beyond the port waters, is also of interest. Martinez Tiburcio (2005) assesses that petroleum facilities in the Campeche Sound continued to be potential targets for international terrorists. He studies the deployment of surveillance and interdiction capabilities to defend against terrorist attacks. He models the attackers and defenders

using MANA. Martinez Tiburcio found that "the most important threat factor in the scenarios is the speed of the enemy boats; and, with its broad surveillance and communication capabilities, the HAWKEYE is the most important navy resource in the area." His study provides operational insights for strategizing naval deployments in the Campeche Sound.

Singh (2010) studies the Israeli coastal defense, as the Israelis have deep experience in dealing with terrorist small boat attackers. He studies various capabilities in enhancing situation awareness of small boat threats in coastal waters. These capabilities cover the Automatic Identification System (AIS), inverse synthetic aperture radar, electro-optical sensors on aerostats, and synthetic aperture radar that are fitted on platforms such as aerostats and low earth orbit satellites. His study determines "the optimum number of aerostats fitted with an appropriate sensor suite" and provides recommendations such as to amend "existing International Maritime Organization AIS fitment policy from size-based to role-based fitment."

From the four studies, it is important to consider both attacker and defender tactics in examining small boat attacks. Agent-based simulations, such as MANA, are found to be useful in modeling the operational scenarios and providing data for analysis. Aerial surveillance, for instance, from airborne early warning aircraft or aerostats, is a key success factor in countering small boat attacks and is considered in this research.

E. ENHANCING POINT DEFENSES ON SHIPS

Other studies look at enhancing point defenses against terrorist small boat attacks. Tiwari (2008) says that an effectiveness gap exists in U.S. Navy ships' abilities to defend against small boat attacks in a crowded strait, particularly due to the difficulty in identifying hostiles from non-hostiles and the short reaction time available for taking defensive actions before getting hit by the attackers. He studies the use of artificial intelligence to model small boat attacks on an Arleigh Burke class destroyer transiting a narrow strait. He identifies and recommends enhancements to overcome gaps in crew training and small caliber weapons (25 mm and smaller). His study provides a basis for

future work to measure the performance of equipment and tactics as part of informing capability and doctrine development.

Abel (2009) finds that small boat attacks posed an increasing challenge to North Atlantic Treaty Organization (NATO) frigates. He uses tools and techniques such as MANA, DOE, linear regression, and partition trees in his analysis. The simulated scenario is an artificial one, comprising a square with the frigate moving from the bottom-left to the top-right corner. The small boat attackers approach from the top-left or bottom-right corner, or both. The attackers' weapons being modeled include the RPG-7 and pistol. The defender's weapons include a frigate with a main gun, an auxiliary gun, a close-in weapon system (CIWS), and a pistol, as well as a helicopter with AGM-114 Hellfire missiles. Abel finds that small boat attackers with handheld weapons can potentially destroy a typical NATO frigate on a patrol mission. He also finds that "a mix of advanced, automated weapons is best suited for close-in defense against multiple small seaborne attackers," as compared to the existing manually-aimed weapons. This would significantly enhance the frigate's mission survival. His study informs capability development.

McKeown (2012) studies the modeling of OPV effectiveness against small boat attackers that used suicide weapons. He also uses MANA as the M&S tool. The modeled scenario is an artificial one, with the OPVs protecting a "goal line" using a barrier patrol. The small boat attackers' objective is to reach the goal line. The attackers are armed with suicide bombs. The defender's weapons include three OPVs each with a main gun and Griffin missiles, as well as one unarmed helicopter providing surveillance. Three types of behavior for the attackers are modeled–aggressive, avoidance or combination. McKeown finds that OPVs needed to be sufficiently equipped with weapons to defend an objective area from an attacking small boat swarm successfully. The type of weapons onboard the OPVs, and the presence of a helicopter providing surveillance, have a significant impact on the simulation results.

Kaymal (2013) evaluates the effectiveness of an OPV in escorting and protecting a high value unit against a terrorist small boat attack. The scenario is a high value unit escort mission taking place in the Strait of Gibraltar. This strait is chosen as a small boat

terrorist attack on two merchant vessels took place in June 2002. The attackers carry suicide bombs. The defender's weapons include an OPV with a main gun, an auxiliary gun, and a machine gun, as well as one helicopter armed with a machine gun. Kaymal uses MANA and DOE to assess the operational effectiveness of the OPV in this scenario. His modeling results show that enabling the OPV main gun, or having a highly-effective auxiliary gun in place of the main gun, are significant factors for mission success. The presence of the helicopter does not show up among the significant factors as the helicopter was not important in every scenario run.

The four works show that studies have been done on modeling and analyzing the close range battle between small boat attackers using short-range weapons and suicide bombs and ships using various guns. This research contributes to the knowledge gap by focusing on the long-range battle between small boat attackers using conventional anti-ship cruise missiles and a carrier group; gun battles are not studied in this research. The use of DOE is observed to be valuable in maximizing insights gained from analyzing the impact of any combination of input parameters on output measures, and in making the experiment efficient. This author concludes that the use of statistical analysis tools, such as the logistic regression model, main effects model, second order model, and partition tree, are valuable in identifying and rank-ordering the significant factors.

F. EXPLOITING NET-CENTRIC MARITIME WARFARE

Marland, Galligan, and Galdorisi (2005) study the impact of four notional levels of network centricity between friendly units on countering attacks from three broad categories of small boat swarm attackers. The four levels are, in a simplified sense, "no datalink," "local datalink," "global datalink," and "co-operative engagement capability." The categories are, broadly, "type 1 RPG/suicide bombs (3-500 m)," "type 2 MLRS rocket (8 km)," and "type 3–missile/torpedo." The model scenario involves a friendly naval convoy transiting a narrow channel populated with fishing and trading vessels. The small boats waited among the neutral vessels to attack friendly units. The type 3 boats are of interest to this research. This study finds that type 3 attackers typically outranged the guns on friendly ships. This means that the friendly force should employ airborne units,

such as organic helicopters or UCAVs, to attack the type 3 attackers—at further distances where the friendly ships will not be threatened. Alternatively, the friendly force needs to enhance its anti-ship missile defenses. Four modeling tools are used, including MANA. The authors find MANA to represent both forces with sufficient detail and to be useful in analyzing such a combat scenario.

Marland, Galligan, and Galdorisi (2005) offer insights on the need for better surveillance, in particular from airborne units, coupled with target reporting to maximize the range that ship weapons can be employed. Additionally, the friendly forces should exploit airborne attacks to destroy, if not reduce the numbers of, enemy boats. Friendly ships should be equipped with weapons with longer ranges to exploit targets found by airborne units at farther ranges.

G. THESIS CONTRIBUTION TO ACADEMIC DISCOURSE

The context of existing counter small boat studies shows that a knowledge gap exists in countering small boat swarm attacks utilizing longer-range weapons, such as anti-ship cruise missiles, in a scenario analogous to the IRGCN training attack on a mock aircraft carrier. This thesis addresses the gap through analyzing possible tradeoffs between weapon consumption, fuel consumption, and costs.

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III. METHODOLOGY

A. INTRODUCTION

This research uses open source and unclassified information to develop a notional scenario and capabilities that could be representative of the real world. A suitably accurate scenario enables meaningful analysis of the trade space—between force protection effectiveness, weapon consumption, fuel consumption, and cost—in countering conventional attacks from small boat swarms. The approach is not to attain an exact representation of real world entities and their behavior. Future work could substitute actual information, including that obtained from defense agencies, contractors, and classified sources, for more precise results.

B. EXPERIMENTATION AS THE RESEARCH METHOD

As a key instrument in the systems engineering approach to study capability requirements, computer experimentation is a powerful and proven method. It is increasingly the primary choice for exploring the decision space of complex problems; in particular, the trade space in a capability portfolio. Experimentation enables analysts to obtain insights by testing different variables, such as force configuration and weapon use policy, with regard to certain performance measures. Such insights identify required capabilities that meet mission objectives.

The operational scenario is a model inspired by the IRGCN 2015 training attack on a mock U.S. Navy aircraft carrier. Baseline capabilities, as well as alternate capability portfolios, are analyzed in terms of force protection effectiveness, weapon and fuel consumption, and financial costs. Computer simulation and DOEs enable systematic changes to input parameters in order to generate output data that can be used for complex analyses. Using actual entities or physical experiments is assessed impractical within the study timespan, cost, and level of effort available.

C. OPERATIONAL SCENARIO AND ENEMY CAPABILITY

The selected operational scenario for building the computer simulation model is the IRGCN 2015 training attack on a mock U.S. Navy aircraft carrier in the Strait of Hormuz. Figure 3 shows this narrow strait between the Persian Gulf and the Gulf of Oman, and its proximity to the Iranian coast. The graphic includes the locations of five nearby Iranian naval bases (in blue) from which the IRGCN small boats can deploy.

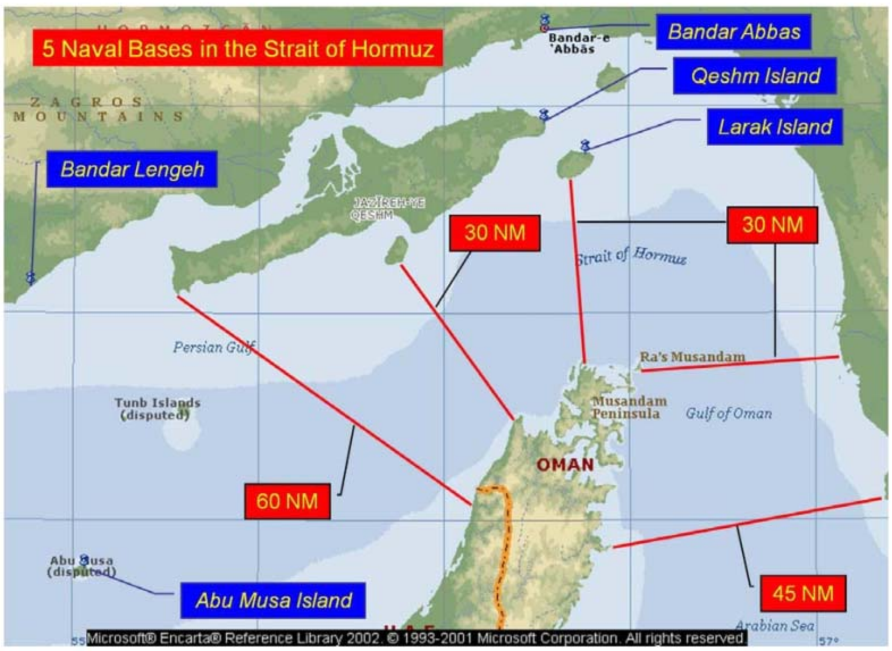


Figure 3. Strait of Hormuz with Nearby Iranian Naval Bases. Source: Ozdemir (2009).

The key assumptions about the IRGCN operations are:

1. Surface threats other than the small boats, submarine, air, and anti-air (e.g., attacks against TUAVs) threats are not modeled.

2. The small boats target only the U.S. Navy carrier as the lucrative, high-reward target, as it is less worthwhile to commit such resources to attack a cruiser or smaller ship. This means sidestepping less lucrative targets, such as a littoral combat ship (LCS) or unmanned surface vehicle (USV), attempting to interfere with their approach to the carrier.

3. The larger Iranian boats (assume > 60 feet), that are more easily detected, avoid getting destroyed by hiding and staying out of the attack (Cordesman 2015, 33).

4. The IRGCN has received intelligence on the carrier group transiting the strait, and hence deploys small boats to position and maneuver for an attack on the carrier.

5. The scenario assumes a swarm mass approaching the target from the north, deployed from naval bases along the Larak Island axis, and a second swarm mass from the west, deployed from naval bases along the Bandar Lengeh axis. Literature show that the IRGCN have learnt from past battles and since adopted a dispersed swarm in a swarm attack (Cordesman and Lin 2015, 33; Gholz et al. 2008; Haghshenass 2006).

6. The small boats are evenly divided between the north and west axes.

7. The small boats operate in an “I see I shoot” manner. They are reported to be lacking in long-range targeting capability, and launch their anti-ship missiles only at ranges where the firer can identify the target (Haghshenass 2008, 13; Cordesman 1994, 70).

8. The small boats each have a navigation radar for target detection, as well as binoculars and night vision devices for target identification. The detection and identification ranges are unknown and are explored in the DOE in Chapter IV.

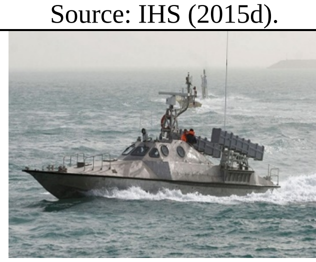
9. The small boats have little or no shared situation awareness, as there is likely no datalink between the small boats.

10. The small boats transit at 25 to 30 kts when on patrol. They increase to 50 kts when investigating and attacking.

11. The C704 ASCM travels at 300 meters per second.

The IRGCN force has a notional composition shown in Table 1. Key parameters on the capabilities and force numbers are compiled from various IHS sources (2015a; 2015d; 2015f).

Table 1. IRGCN Small Boat Swarm Composition.

<table>
<tr><th>Quantity & Class</th><th>Image</th><th>Length</th><th>Top Speed</th><th>Main Weapon</th><th>Remarks</th></tr>
<tr><td>5 × C-14</td><td>
Source: IHS (2015a).</td><td>13.8 m</td><td>50 kts</td><td>4 × C-704 missile (38 km range)</td><td rowspan="3">- no main or auxiliary gun observed
- small radar observed
- C-704 has 130 kg warhead (cf. Exocet AM39 with 165 kg warhead that hit USS Stark)</td></tr>
<tr><td>10 × Mk 13</td><td>
Source: IHS (2015d).</td><td>13.5 m</td><td>60 kts</td><td>4 × C-704 missile (38 km range)</td></tr>
<tr><td>29 × Peykaap II</td><td>
Source: IHS (2015f).</td><td>17.3 m</td><td>52 kts</td><td>2 × C-704 missile (38 km range)</td></tr>
</table>

For the friendly force, the key assumptions about its operations are:

1. It has to transit from the Gulf of Oman (East of Strait of Hormuz) to the Persian Gulf (West of Strait of Hormuz) for a conventional warfare mission. While on transit, the force encounters a surprise conventional attack from the IRGCN small boat swarm.

2. It transits along the southern part of the strait to maximize stand-off distance from threats emanating from the Iranian coast.

3. The carrier group, comprising one aircraft carrier (CVN), one guided missile cruiser (CG), two guided missile destroyers (DDG) and one oiler (AOR), transit the strait together at the top speed, 20 kts, of the slowest ship, the AOR. There are no changes in speed and route when attacked.

4. The carrier group has superior long-range shared situation awareness (> 50 nm) on incoming anti-ship missiles in the narrow strait (30 nm). This is enabled by advanced radar, C3, and datalink capabilities.

5. Friendly units have situation awareness on one another’s location and movement through datalink.

6. The carrier group will shoot incoming C704 missiles using the longest range SAM (SM-2) followed by the medium range SAM (ESSM) and then the close range SAM (RAM). The maximum and minimum ranges for each type of SAM are modeled.

7. The vertical launcher cells in the CG and DDGs are assumed loaded with SM-2 and ESSM missiles. In actual missions, there could be a mix of Tomahawk, ESSM, and various types of SM missiles.

8. A salvo size of one SAM (as opposed to two or more) is used against each incoming C704 missile.

9. A salvo size of one missile (as opposed to two or more) is used against each enemy small boat. A successful hit is assumed to destroy a small boat.

10. The use of the Phalanx CIWS gun to shoot incoming missiles is not modeled. The C704 ASCMs are modeled to target only the CVN, which is not installed with the Phalanx CIWS gun.

11. The LCS, USV, and tactical unmanned aerial vehicle (TUAV) increase in speed when investigating. They proceed at maximum speed when attacking. The modeling of different speeds leads to more accurate calculations of fuel consumed in the small boat battle.

12. The TUAV shares its situation awareness of unknown and enemy targets with the USV and LCS. The USV shares its situation awareness of unknown and enemy targets with the LCS. The LCSs and USVs proceed at maximum speed towards enemy targets identified by the TUAVs.

13. At the scenario start, the LCSs, if present, are positioned ahead of the carrier group. The TUAVs and USVs, if present, are positioned ahead of the LCSs.

The next section discusses the friendly force capabilities analysis. Other key scenario assumptions for the reader’s attention are:

1. Gun battles (5000 m or closer as a guide) are not modeled as these have been studied in previous literature (such as Abel 2009; McKeown 2012; Kaymal 2013).

2. The strait is assumed to be temporarily free of neutral shipping as conflict has taken place. Innocent civilians would want to avoid becoming collateral damage. Future work can include modeling neutral traffic for added complexity.

D. FRIENDLY FORCE CAPABILITY PORTFOLIO OPTIONS

The approach for establishing a capability baseline uses today’s cutting-edge technologies. This serves to provide insights on the gaps in today’s capabilities and acts as the reference for comparing alternatives. With regard to the U.S. Navy (2016), the baseline capability is defined as a typical carrier group comprising a CVN (Nimitz class), a CG (Ticonderoga class), two DDGs (Arleigh Burke class), and an AOR (Henry J Kaiser class). The submarine is excluded as undersea warfare is not in this research’s scope. Table 2 contains the key capability parameters compiled from various IHS sources (2015e; 2016a; 2016d; 2016h).

Table 2. Baseline Capability Key Parameters.

Quantity & Class	Image	Top Speed	Modeled Weapons	Remarks
1 × CVN	 Source: IHS (2015e).	30 kts	16 × ESSM (0.5 to 18.5 km range; 2 shots per sec) 42 × RAM (0.5 to 9.6 km range; 2 shots per sec)	Both maximum and minimum ranges are modeled. It is not realistic to have SAMs engage targets beyond these ranges. Notional firing rates are assumed and required in the MANA settings.
1 × CG	 Source: IHS (2016h).	30 kts	90 × SM-2 (7.4 to 167 km range; 2 shots per sec) 32 × ESSM (0.5 to 18.5 km range; 2 shots per sec)	
2 × DDG	 Source: IHS (2016a).	31 kts	96 × SM-2 (7.4 to 167 km range; 2 shots per sec) 32 × ESSM (0.5 to 18.5 km range; 2 shots per sec)	
1 x AOR	 Source: IHS (2016d).	20 kts	No anti-air weapon	

Note: The submarine was excluded as undersea warfare is not within the scope of this research.

Additional capability options are examined as augmentation, assuming the carrier group is critically needed, as a whole set, to fulfill the primary mission post small boat swarm battle. The method of identifying alternate options is adapted from the Building Blocks to Composite Options Tool (BCOT) developed by RAND Corporation (2008, 39). RAND created this tool to maximize exploration of the composite options space. The tool intends to identify better-performing composite options that might have been left undiscovered if a less sophisticated manner of proposing composite options is used. The term “composite option” is used in this research to refer to the combination of the baseline and added capabilities. The BCOT, depicted in Figure 4, first identifies individual capability components or “building blocks,” such as a ship, aircraft, or weapon. Second, numerous composite options are generated from various combinations of the building blocks. Third, the composite options are modeled and analyzed, for this research, in terms of force protection effectiveness, weapon and fuel consumption, and cost. Fourth, the screened options are identified from the slew of composite options. Steps two through four are discussed in Chapter IV. This author expects that the screened options would be on or close to the Pareto efficient frontier (PEF) curve (see Figure 5) defined as a conceptual curve that connects data points that are at least as effective as any other data point with the same horizontal axis value (39).

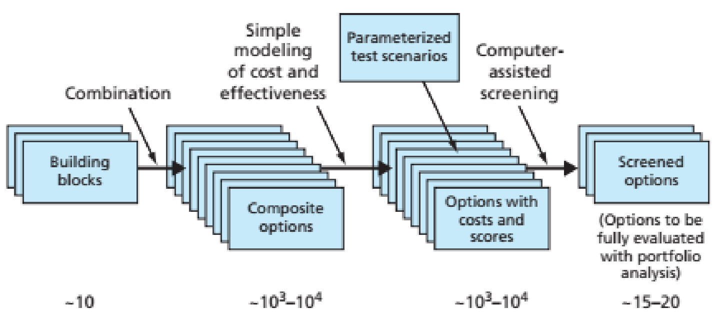


Figure 4. Schematic of BCOT. Source: Davis, Paul, and Beck (2008, 39).

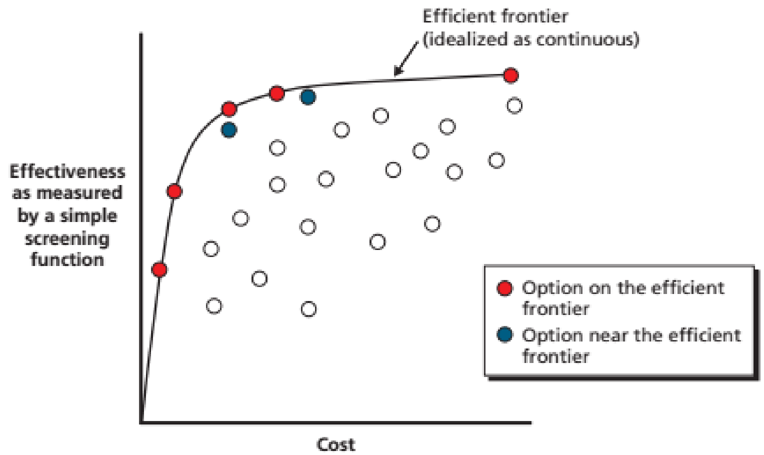


Figure 5. Schematic Depiction of Finding Points near the Efficient Frontier.
Source: Davis, Paul, and Beck (2008, 40).

The building blocks against small boat attacks are options that were likely to mature within the next five to ten years. This timeframe would then be useful for decision making in the immediate term (present to next five years). The results of this study could lead to more efficient ways of countering the IRGCN small boat swarm or similar attack scenarios. The identified building blocks are a notional set, and represent a good spread of options across surface/airborne and manned/unmanned platforms. This notional set is not meant to be exhaustive, but is representative of maturing technologies. A literature survey reveals the following building blocks.

The AGM-114L Longbow Hellfire has been modified to represent the surface-to-surface missile module (SSMM) on either LCS class, according to IHS (2015g). Each SSMM contains 24 Hellfire missiles. The modified Hellfire missiles, with a range of 8.3 km, were test fired at sea in June 2015. The SSMM is expected to be deployed in late 2017.

Another building block is the 11 m USV armed with Spike LR missiles. According to IHS (2012), this is a project developed to deal with asymmetric swarm boat attacks. The proof-of-concept demonstration occurred in October 2012. Related to this development is the testing of “autonomous control of at least five USVs for escort and attack missions” in 2014 by the U.S. Office of Naval Research (ONR) (Brizzolara 2015).

In this research, composite options of up to five autonomous 11 m USVs armed with Spike LR missiles are studied. Non-autonomous USVs are not considered so that standalone USV operations can be explored. The USVs are assumed deployed from another ship if not carried by the LCS.

A third system to be considered is the Fire Scout MQ-8B TUAV armed with APKWS missiles. The APKWS uses 70 mm rockets modified with laser guidance. According to IHS (2016h), the APKWS was being integrated into the Fire Scout as of 2012. In 2013, the APKWS was test-fired at sea against high speed surface targets (IHS 2016a).

Table 3 summarizes the key capability parameters of each building block compiled from various IHS sources (2012; 2016d; 2016h). Some may argue that laser weapons and manned helicopters should be included in the building blocks. This author assessed that laser weapon technology would not mature at least for the next ten to fifteen years. In a study on “Viable Short-Term Directed Energy Weapon Naval Solutions” (Team Bravo Cohort 19 2013, 101), it was found that the maximum effective range against a 2-cm-thick aluminum-hull small boat moving at 45 kts was at best 1000 m. This is not effective against small boats that can launch anti-ship missiles at much greater ranges. The manned helicopter, on the other hand, can be represented by the TUAV as a surrogate. Furthermore, involving one or more manned helicopters could place additional risk on human lives if anti-air threats are present. A TUAV will have no loss of onboard aircrew if shot down.

Table 3. Building Block Capability Key Parameters.

Building Block	Image	Top Speed	Modeled Weapons	Remarks
LCS with modified Hellfire missiles	 Source: Eshel (2015).	40 kts	24 × Hellfire (0.5 to 8.3 km range)	Up to 12 Freedom class LCSs are explored in this research. Future work could include the Independence class LCS in the M&S.
Autonomous 11 m USV with Spike LR missile	 Source: Defense-Aerospace (2012).	40 kts	2 × Spike LR (0.2 to 4 km range)	Up to 5 Spike-USVs are explored in this research—limited by autonomous control technology.
Firescout MQ-8B with Advanced Precision Kill Weapon System II	 Source: Osborn (2013).	125 kts	12 × APKWS (1.1 to 5 km range)	Up to 24 TUAVs are explored in this research. 12 LCSs could only carry up to 24 TUAVs.

Chapter IV of this thesis systematically explores various values for the unknown capability parameters. These include the detection ranges and identification ranges for the LCS, USV, and TUAV, as well as the hit probabilities for the SM-2, ESSM, RAM, Hellfire, Spike LR, and APKWS missiles. Although the actual parameter values are unknown, a methodical study of them provides important information about the range of values that have significant influence on the performance measures of interest.

E. MODEL DEVELOPMENT

This research involves a large-scale simulation. This type of simulation typically varies hundreds or thousands of factors, and with multiple levels per factor. Efforts, such as by Powers, Sanchez and Lucas (2002) and Sanchez et al. (2012), advocate the use and benefits of large-scale simulation experiments, enabled by technological advances in computing power, to provide powerful insights from such experiments. A small-scale

simulation experiment involving only a few factors is likely to produce fewer insights because of its limited scope. A large-scale study with factors varied in an ad hoc manner cannot be used to identify the most important factors, while one wherein each factor is varied one at a time cannot reveal how the performance changes when the factors are varied together (Sanchez and Wan 2015).

There are several reasons for using MANA, a simulation software developed by the New Zealand Defence Technology Agency. MANA employs agent-based simulation. This type of simulation captures unanticipated results that may arise from behavioral interactions between agents (e.g., ships, small boats, USVs and TUAVs). MANA is designed as a distillation model that eliminates unnecessary complex computations (e.g., missile ballistics) but can adequately produce required data for complex analysis. Compatibility with the Naval Postgraduate School's SEED Center suite of data farming tools is also important. The Center has a powerful computing cluster that can execute large-scale MANA simulation experiments, as well as automate the varying of parameters in each simulation run and the processing of output data. Previous theses that analyze capability effectiveness and use MANA, such as in Abel (2009), McKeown (2012), and Kaymal (2013), also show the useful application of this tool. MANA-V version 5.09.04 is used. Figure 6 shows the snapshot of a simulation run that incorporated the operational scenario, capabilities, and key assumptions.

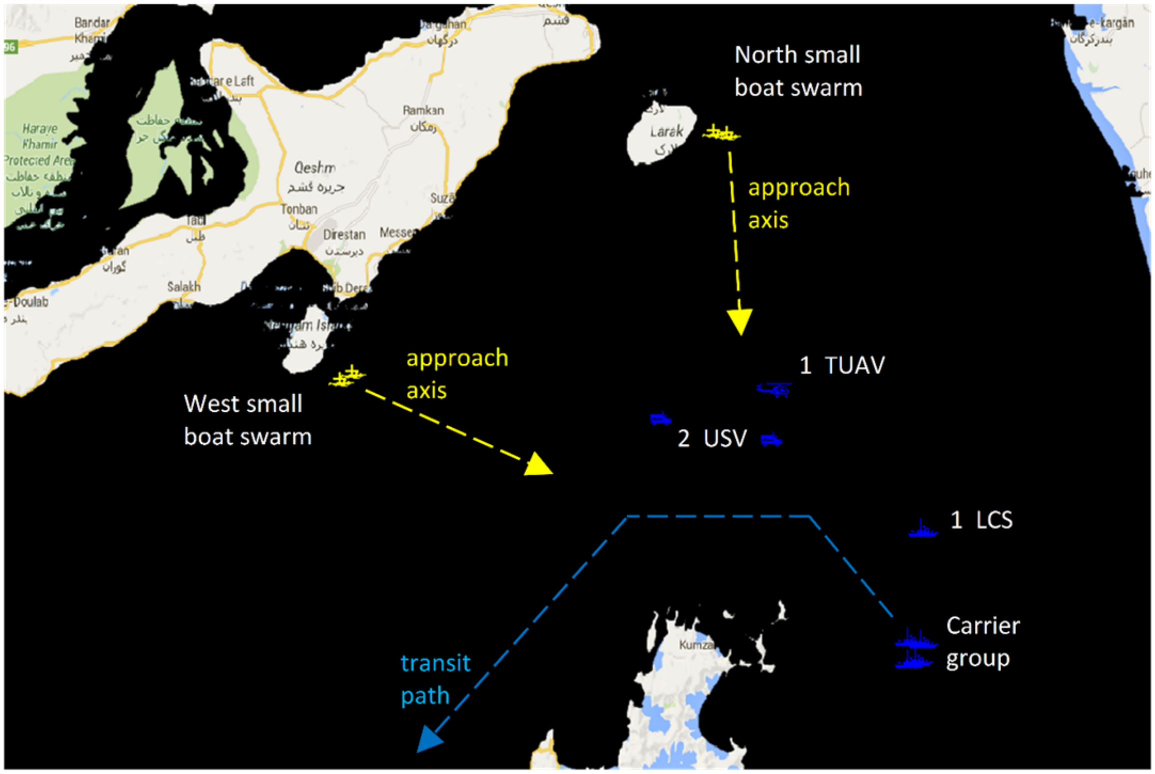


Figure 6. Snapshot of a Simulation Run in MANA.

The simulation constraints and settings in MANA could have had some influence on the model results. These key constraints and settings are:

1. Combat exchanges could sometimes involve multiple attacks on the same target by multiple units or by more than one weapon from the same unit. This would make the number of expended weapons larger than if using a one-weapon-at-a-time-per-target rule. Kill assessment is instantaneous and prevents any further multiple attacks.

2. A model time step of 1.0 s is used. Each run (battle) ran for 4500 s (one hour and fifteen minutes), without a stop condition, in simulation time. All combat exchanges typically complete by about 4000 s.

3. A simple mode for line-of-sight calculations is used. This is adequate for modeling the TUAV operating in the air and all vessels operating at sea level.

4. The weapons of the different platforms are set to fire at the nearest valid target when there is more than one target.

5. The sensor detection and classification (identification) ranges used the cookie-cutter mode. A valid target is detected/classified with a probability of one when within range. The sensor detection and classification ranges are, however, varied in the experiment.

6. The weapon hit probabilities used the cookie-cutter mode. A single hit probability value is uniformly applied over the minimum to maximum range of the weapon.

7. Each run used a different random seed.

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IV. MODEL EXPLORATION AND DATA ANALYSIS

A. INTRODUCTION

The MOEs address the research questions in this thesis. Two or more measures of performance (MOP) support each MOE. Each MOP quantifies the performance of a capability portfolio option with respect to its attributes, along with data requirements to enable its measurement. The DOE maximized insights from the simulation experiment and ensured simulation completion within a practical time. This study examines factors under the general categories of "adding capabilities," "varying tactics," or "exhibiting uncertainty." The simulation runs and open literature provide data for analysis. We used statistical analysis tools in JMP to derive insights on any cause-and-effect between the input factors and MOPs.

B. MEASURES OF EFFECTIVENESS AND PERFORMANCES

The MOEs are linked directly to the critical operational issues and appraise how well a system meets mission objectives under a given set of circumstances (Stevens 1986, 36). With reference to Stevens' guidance on writing good MOEs (55), each of the three COIs has an associated MOE defined as follows:

1. How well does the capability portfolio option ensure force protection?
2. How efficient is the capability portfolio option in terms of weapons and fuel consumption?
3. How cost-efficient is the capability portfolio option?

The MOPs are defined based on three considerations. Each MOP has to be relevant to the MOE. The data required for each MOP has to be obtainable, in this case, from the MANA modeling and open data sources. All MOPs are formulated so that, visually, lower is better on charts. Table 4 lists the MOEs, MOPs, and data requirements.

Table 4. Measures of Effectiveness, Measures of Performance and Data Requirements.

MOE	MOPs	Data Requirements
1. How well does the capability option ensure force protection?	1. How many missile leakers occurred?	a. Number of C704 missile leakers that reached CVN.
	2. How many enemy boat leakers occurred?	b. Number of enemy boat leakers that reached 4 km of CVN
2. How efficient is the capability option in weapon and fuel consumption?	3. % of total SM-2 used?	c. Number of SM-2 used d. Number of SM-2 carried
	4. % of total ESSM used?	e. Number of ESSM used f. Number of ESSM carried
	5. % of total RAM used?	g. Number of RAM used h. Number of RAM carried
	6. % of total Hellfire used?	i. Number of Hellfire missiles used j. Number of Hellfire missiles carried
	7. % of total Spike used?	k. Number of Spike LR missiles used l. Number of Spike LR missiles carried
	8. % of total APKWS used?	m. Number of APKWS missiles used n. Number of APKWS missiles carried
	9. LCS & USV fuel used?	o. Time spent at different speeds for each LCS and USV p. Fuel consumption data for LCS and USV
	10. TUAV fuel used?	q. Time spent at different speeds for each TUAV r. Fuel consumption data for TUAV
3. How cost-efficient is the capability option?	11. Cost of total weapons used?	c. Number of SM-2 used e. Number of ESSM used g. Number of RAM used i. Number of Hellfire missiles used k. Number of Spike LR missiles used m. Number of APKWS missiles used s. Unit cost for each type of missile
	12. Cost of additional platforms?	t. Number of LCSs deployed u. Number of USVs deployed v. Number of TUAVs deployed w. Unit cost for each type of platform

Under MOE 1, two MOPs are defined. MOP 1 measures the number of C704 leakers that reach the CVN. Leakers occur when there are more incoming missiles than the carrier group’s SM-2, ESSM, or RAM can counter within the constraints of the respective engagement envelopes. Measuring the probability of CVN survival is a separate and more complex study left for follow-on research, although MOP 1 results could become inputs to such a study for further analysis. On considering the number of C704 being launched and the proportion of C704s that leaked, these are deemed not useful as compared to the number of C704 leakers. The number of C704 being launched

closely correlates with the number of small boat leakers, which is defined as MOP 2. The proportion of C704 leakers could mask the magnitude of the problem. For instance, there could be a low proportion of leakers even though there was a significant number of leakers. MOP 2 measures the number of enemy small boat leakers. This is defined as the number of enemy small boats that reach within 4 km of the CVN. The notional 4 km represents a suitable transition to a battle involving handheld/shoulder-launch weapons, suicide explosives, or both, with the CVN. These close-range battles have been modeled in other studies (Abel 2008; McKeown 2012; Kaymal 2013). The MOP 2 results could become inputs to similar future studies for further analysis. MANA is configured to provide data for data requirements a and b.

For MOE 2, eight MOPs were defined. MOPs 3 to 8 measure the proportion of friendly missiles used. The MOPs 3 to 5 are for each type of SAM. The MOPs 6 to 8 are for each type of missile used against the enemy small boats. The formulas for MOPs 3 to 8 are the number of missiles used divided by the total number of the same missile carried by the force. The use of proportion of missiles for MOPs 3 to 8 provides a good sense of missiles used and missiles remaining in the force, as compared to the expended or remaining number of missiles. MANA output data meets data requirements c, e, g, i, k, and m. Data for requirements d, f, h, j, l, and n are calculated from the input factors.

Still under MOE 2, MOPs 9 and 10 measure the fuel consumed by all LCSs and USVs, as well as all TUAVs respectively. The fuel consumed by the baseline capability (i.e., the ships in the carrier group) is not measured, as the composition and speed of the carrier group is invariant across all capability options being analyzed. These ships move at a nominal speed of 20 kts, the maximum speed of the oiler. The total fuel consumed by the added force depended on the speed and components of the added force. The formulas for the two MOPs are the speed of each platform multiplied by the associated fuel consumption rate. MANA is configured to provide the time spent at the different speeds in meeting data requirements o and q. Notional data sources meet data requirements p and r. Table 5 shows the different nominal speeds modeled for the LCS, USV, and TUAV, and the associated fuel consumption rates.

Table 5. LCS, USV and TUAV Modeled Speeds and Fuel Data.

Platform	Behavior	Nominal Speed	Fuel Consumption Rate	Remarks and Data Source
LCS	Transiting	25 kts	1500 U.S. Gal / hour	From the average of the CLWP and PEO curves in Baggett (2008, 37, Figure 9).
	Investigating contact	30 kts	2050 U.S. Gal / hour	
	Attacking enemy	40 kts	3500 U.S. Gal / hour	
USV	Transiting	25 kts	10 U.S. Gal / hour	From the fuel performance table of a proxy vessel (a dual engine 7 m speedboat) in Boattest (2015).
	Investigating contact	30 kts	12 U.S. Gal / hour	
	Attacking enemy	40 kts	20 U.S. Gal / hour	
TUAV	Transiting	80 kts	95 lb / hour	100 lb/hr from Ong (2014, 24) is assumed for 100 kts. 5% decrease is assumed for 80 kts. 10% increase is assumed for 125 kts.
	Investigating contact	100 kts	100 lb /hour	
	Attacking enemy	125 kts	110 lb /hour	

On MOE 3, two MOPs were defined. MOP 11 measures the cost of all friendly missiles used. This is a good measure of the cost of expendables (less fuel). MOP 12 measures the cost of the added platforms. Platforms are typically costly, much more than expendables, and should be examined. The cost of the baseline capability is not included as it is invariant across all capability options being analyzed. The formulas for the two MOPs are the number of weapons/platforms multiplied by the associated unit costs. MANA supplies data to meet requirements c, e, g, i, k, and m. Data for requirements t, u, and v are calculated from the input factors. Table 6 shows the notional unit costs used to meet data requirements s and w. The cost figures, being nominal, are not normalized to the same fiscal year. The base years range from FY06 to FY15, but could be normalized in a follow-on study.

Table 6. Unit Cost Data for Weapons and Platforms.

Weapon / Platform	Notional Unit Cost	Remarks and Data Source
SM-2	$750,000	Assumed Block IIIA. Source: Deagel (2015).
ESSM	$905,000	Assumed average of Mk 29 and Mk 41 variants. Adapted from Oestergaard (2014a).
RAM	$760,000	Assumed Block 2. Source: Oestergaard (2014b).
Hellfire	$99,600	Source: Balle (2015a).
Spike LR	$153,000	Javelin AAWS-M used as proxy. Source: Balle (2014).
APKWS	$33,200	Assumed 1/3 cost of Hellfire missile, according to Sax (2013).
LCS	$476,000,000	Source: Balle (2015b).
TUAV	$10,800,000	Assumed Fire Scout MQ-8B. Source: Balle (2015c).
11 m USV	$6,350,000	11 m anti-submarine warfare Protector USV is used as proxy. Source: IHS (2006).

C. FACTORS

Factors are input parameters of interest that are changed during the experiment. These parameters are examined, through the analysis that follows the experiment, for any impact on the MOPs. Controllable factors can be changed, for example, by a decision maker. Uncontrollable factors are parameters with unknown information or over which a decision maker has little or no control.

1. Adding Capabilities (Controllable)

This set of factors encompasses adding capabilities to the baseline capability (see Table 7). Factors 1 to 3 are the numbers of added LCSs, USVs, and TUAVs, respectively. Each combination of the three factors represents a composite option mentioned in Chapter III. The number of TUAVs is a multiplier of the number of LCSs, as the former is assumed to be carried and deployed from the latter. The lower limits represent no added capability. The upper limit for the LCS is based on the number of Freedom class LCS in the Orbat reported by IHS (2016d). For the USV, the upper limit is based on an ONR article that autonomous operation of at least five USVs was achieved (Brizzolara 2015). The upper limit for TUAVs is based on up to two TUAVs carried per LCS (IHS 2016d).

Table 7. Factors Testing Impact of Adding Capabilities.

No.	Factor	Lower Limit	Upper Limit	Remarks
1.	No. of LCSs	0	12	High limit based on Freedom class Orbat (IHS 2016d)
2.	No. of USV	0	5	High limit based on current limit of autonomous technology (Brizzolara 2015)
3.	TUAV multiplier of no. of LCSs	0	2	Variable is multiplier of number of LCSs. Each LCS carries up to two TUAVs (IHS 2016d)

2. Varying Tactics (Controllable)

The second set of factors represents the use of tactics to improve MOP results (see Table 8). Factors 4 to 9 are the different SAMs constrained by decision for use in combat. The ships would still carry full loads of SAMs. Factors 4 to 9 examine if conserving the use of SAMs, whether as a single factor or when combined with other factors, has any positive or negative impact on weapon consumption and other MOPs. The low limits are set at zero, while the upper limits are set at the maximum load, to see if interesting insights can be gained. For this study, the vertical launcher cells for the CG and DDG are assumed to be fully loaded with SM-2s and ESSMs. In a mission, the launcher cells can typically carry a mix of SM-2, SM-3, SM-6, Tomahawk, and ESSM missiles.

Factor 10 examines arming the TUAV with the APKWS missiles. If there would be no significant MOPs gains, freeing the TUAV from the weight of the missiles would allow more flight time for target reconnaissance.

Table 8. Factors Testing Impact of Varying Tactics.

No.	Factor	Low Limit	High Limit	Remarks
4.	CVN ESSM allowed	0	16	Baseline is 16 (IHS 2015e)
5.	CVN RAM allowed	0	42	Baseline is 42 (IHS 2015e)
6.	CG SM-2 allowed	0	90	Baseline is 90 (IHS 2016h)
7.	CG ESSM allowed	0	32	Baseline is 32 (IHS 2016b)
8.	DDG SM-2 allowed	0	96	Per DDG; baseline is 96 (IHS 2016a)
9.	DDG ESSM allowed	0	32	Per DDG; baseline is 32 (IHS 2016a)
10.	TUAV armed?	No	yes	Not arming can increase flight time for surveillance

3. Unknown Information or Uncontrollable

The third set of factors covers key parameters with unknown values or which cannot be controlled by a simple decision (see Table 9). Factors 11 to 16 are the hit probabilities for each type of friendly force missile. Specified hit probabilities could not be obtained. However, the range of probabilities listed is reasonable and could provide significant qualitative insights on how such factors influence the MOPs. This rationale is applied in all cases in exploring the different factors. Operating conditions, such as electromagnetic wave attenuation, target presentation and target maneuvers, could affect each missile’s actual performance. Notional ranges are used to account for variations and add robustness to the modeling. The range of probabilities for the SAMs is set narrower and higher than that for missiles used against enemy small boats.

For the TUAV, LCS, enemy small boat, and USV, factors 17 to 20 are the multiplier values of the respective platform’s classification range. This is used to calculate the respective platform’s detection range. Factors 21 to 24 are the respective platform’s classification range. The ranges in factors 17 to 24 are against surface contacts. In this study, “detection” is knowing the presence of a contact whereas “classification” is differentiating between friend, foe, or neutral. There are two considerations in assigning the notional ranges. First is the relative magnitude between the different platforms. The TUAV, being an airborne platform, would have a longer

sensor range than the three vessels. The LCS is a large vessel that would have longer sensor ranges than the two smaller vessels. The enemy small boat, at 15 m length, would have a longer sensor range than the 11 m USV. Second is that a platform's detection range is longer than the respective classification range.

Factor 25 adds robustness to the modeling by accounting for the possibility of enemy boats being more than that reported by IHS (2015a; 2015d; 2015f).

Table 9. Testing Impact of Uncontrollable and Unknown Factors.

No.	Factor	Low Limit	High Limit	Remarks
11.	SM-2 P_hit	0.7	0.99	SM-2. ESSM, and RAM set at higher range than Hellfire, Spike and APKWS
12.	ESSM P_hit	0.7	0.99	
13.	RAM P_hit	0.7	0.99	
14.	Hellfire P_hit	0.5	0.99	
15.	Spike P_hit	0.5	0.99	
16.	APKWS P_hit	0.5	0.99	
17.	TUAV detection range	1	2.5	Value is multiplier of classification range; to ensure detection range is always greater than classification range
18.	LCS detection range	1	2.5	
19.	Enemy boat detection range	1	2.5	
20.	USV detection range	1	2.5	
21.	TUAV classification range	8000	14000	In meters; TUAV should have the longest range, followed by LCS (large ship), enemy boat, then USV.
22.	LCS classification	7000	13000	
23.	Enemy boat classification range	6000	12000	
24.	USV classification range	5000	11000	
25.	Enemy boats multiplier	1	2	Value is multiplier of enemy boats

D. DESIGN OF EXPERIMENT

A time-efficient and exploration-maximizing DOE to examine all 25 factors is needed in reaping important insights. Running a full factorial experiment, one that explores every possible combination of different factor values, will take too long to complete. For instance, experimenting with two levels for each of the 25 factors will result in 2^{25} or 33,554,432 design points (and most of the 25 factors in this experiment have more than two levels). Each design point is a certain combination of factor levels. If a design point took one second to run, a 2^{25} full factorial experiment will take about 388 days to complete. In contrast, a 512-design point experiment with 50 replications per design point will take about seven hours. Poor design practices, such as varying one

factor at a time or excluding certain combinations of factor values, can prevent important experiment insights from being uncovered (Sanchez and Wan 2015). To maximize insights and complete the experiment within a reasonable time, studies, such as Sanchez and Wan (2015), have shown that the experiment must be designed in a smart manner through the use of an efficient space-filling design.

This experiment uses the 512-design point nearly orthogonal and balanced (NOB) design developed by Vieira Jr et al. (2013). Such a design can accommodate large numbers of discrete and continuous variables along with associated levels, as compared to, for example, use of the nearly orthogonal Latin hypercube (NOLH) design. A consideration for this analysis is that a NOLH design might result in fewer insights due to the inclusion of discrete variables with limited levels (Sanchez and Wan 2015).

The NOB spreadsheet, available from the SEED Center's website at http://harvest.nps.edu, facilitates the creation of custom designs by having the analyst type in the low and high levels for each factor. In this study, for factors that are continuous variables, extending the limits by 0.49 and then rounding results in slightly better boundary coverage by the experimental design.

A 513th design point for the baseline case is added to the 512-design point set (see Table 10). This is important because this study seeks to identify capability portfolios that are as effective as or more effective than the baseline, while simultaneously reducing the weapons cost and energy required. The largest pairwise correlation for the 513 design points had a magnitude of 0.0261, which shows the nearly orthogonal property of the 513-design point set. Near-orthogonality is advantageous for analysis purposes.

Table 10. Baseline Capability Added as 513th Design Point.

No.	Factor	Baseline Value	Remarks
1.	No. of LCS	0	No added capabilities
2.	No. of USV	0	
3.	No. of TUAV	0	
4.	CVN ESSM allowed	16	No restrictions on use
5.	CVN RAM allowed	42	
6.	CG SM-2 allowed	90	
7.	CG ESSM allowed	32	
8.	DDG SM-2 allowed	96	
9.	DDG ESSM allowed	32	
10.	TUAV armed	-	Not applicable
11.	SM-2 P_hit	0.85	Assumed mid-point value between low limit and high limit.
12.	ESSM P_hit	0.85	
13.	RAM P_hit	0.85	
14.	Hellfire P_hit	0.75	
15.	Spike P_hit	0.75	
16.	APKWS P_hit	0.75	
17.	TUAV detection range	1.75	
18.	LCS detection range	1.75	
19.	Enemy boat detection range	1.75	
20.	USV detection range	1.75	
21.	TUAV classification range	11000	
22.	LCS classification	10000	
23.	Enemy boat classification range	9000	
24.	USV classification range	8000	
25.	Enemy boats multiplier	1	Assumed as per reported by IHS (2015a; 2015d; 2015f)

Each design point is replicated 50 times; this was a good balance between achieving a suitable sample size and completing the experiment in a timely manner. MANA uses a different random seed in each replication to have slight differences in force starting dispositions (within a predetermined box) and to calculate weapon engagement outcomes. The mean MOP results across the 50 replications are used in the data analysis. Percentiles of the distribution could be used instead of means in a follow-on study.

E. REGRESSION ANALYSIS METHOD

The partition tree analysis is used to screen the important factors, with significant influence on the MOPs, apart from the rest. The analysis is done using JMP Pro 12.0.1, a

statistical software from SAS. Use of other regression analysis methods is not necessary since this study did not intend to fit linear or non-linear models to the results. JMP's partition tool creates an optimum split in the tree using the factor and factor value that could best explain the variation in the output results (Sall, Creighton, and Lehman 2005). A split recursively builds on the result of the prior split, if any. The decision tree method in the partition tool is used, where a single pass is made through the data to produce a single tree.

Four splits are done. This is a balance between attaining good predictions and overfitting. From the partition analysis, each significant factor's contribution to R^2 is captured in a results table. The R^2 value is the amount of variability in a MOP result that could be explained by the four splits and associated significant factors.

A snapshot of the JMP partition analysis output for the number of C704 missile leakers that reach the CVN is shown in Figure 7. The individual contribution to R^2 is calculated from the R^2 value (highlighted in red) multiplied by the respective proportion value (circled in red). Factors without significant influence have zero proportion values (circled in green; rest of non-significant factors are truncated in Figure 7). Besides the strength of the contribution to R^2, it is important to know whether the correlation is positive or negative. This is determined from examining whether a higher factor level leads to a higher mean value (positive correlation) or lower mean value (negative correlation). For the example in Figure 7, the partition branches (circled in blue) show a negative correlation for the number of LCS factor and a positive correlation for the enemy boats multiplier factor.

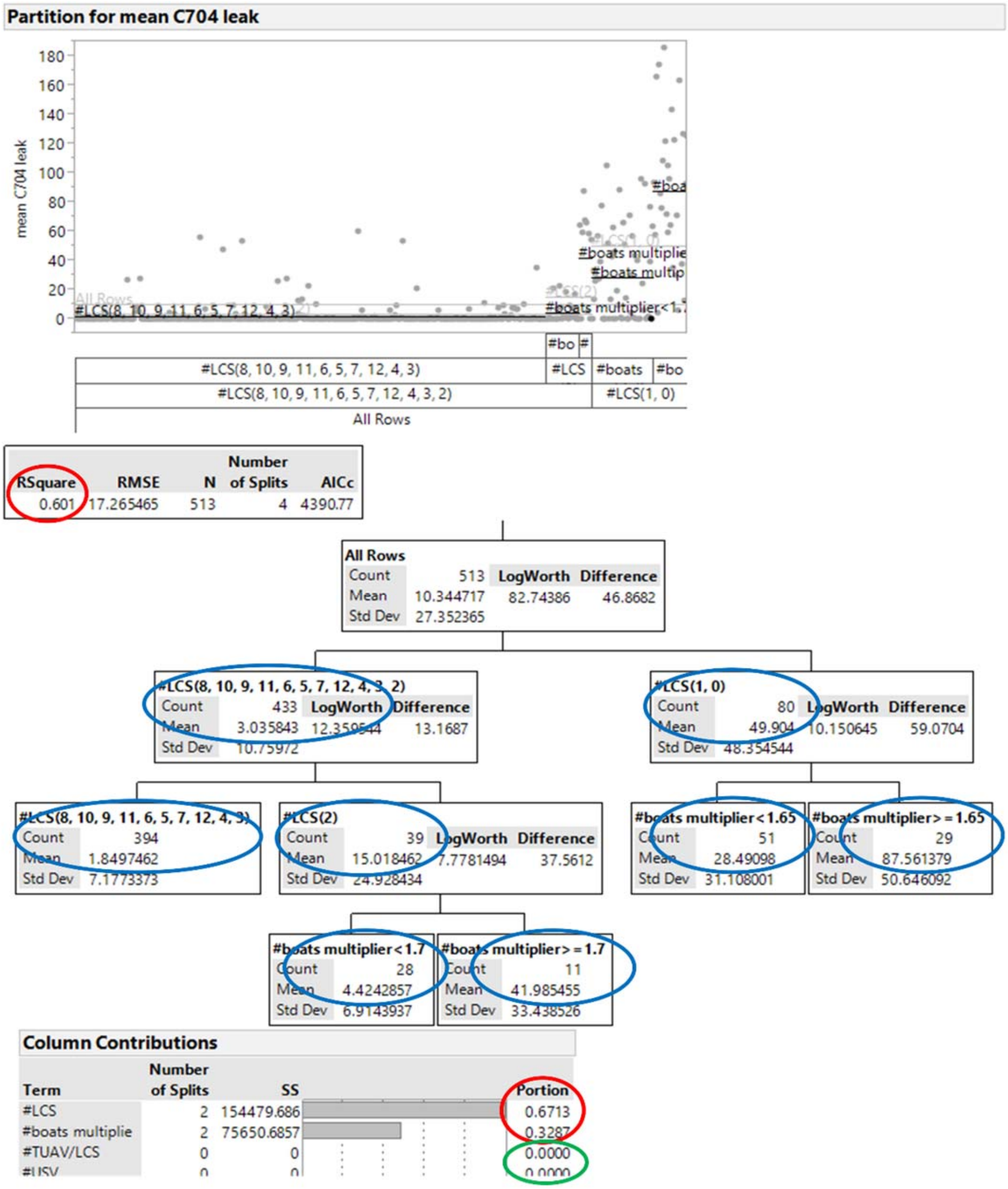


Figure 7. Example of R^2 Contribution Calculation in JMP.

F. RESULTS OF EXPERIMENT ONE

The R^2 contributions from the significant factors in the first experiment are summarized in Table 11, with factors in rows and MOPs in columns. A color banding is used to accentuate the different values — those with strong influence (≥0.40), moderate

influence (≥0.10 and <0.40), and weak influence (<0.10) appear in font color blue, green, and black, respectively. The minus sign implies negative correlation between the factor and the MOP. Throughout this study, the TUAV armed factor associates a “yes” value with a higher level—a minus sign means that “yes” led to a lower MOP result.

Table 11. Experiment One—Influential Factors and R^2 Contributions.

Experiment #1	MOP											
	1. mean c704 leakers	2. mean boat leakers	3. mean SM-2 %used	4. mean ESSM %used	5. mean RAM %used	6. mean Hellfire %used	7. mean Spike %used	8. mean APKWS %used	9. mean LCS & USV fuel used	10. mean TUAV fuel used	11. mean $M wpns used	12. mean $M added force
Controllable factors												
1. #LCS	- 0.40	- 0.81	- 0.27	- 0.32	- 0.33	- 0.55	- 0.12	- 0.38	0.90	0.40	- 0.42	0.96
2. #USV												
3. #TUAV/LCS						- 0.06	- 0.16	- 0.30		0.38		
4. TUAV armed?						- 0.17	- 0.35				- 0.03	
5. CVN ESSM allowed												
6. CVN RAM allowed					0.20							
7. CG SM-2 allowed			0.34								0.12	
8. CG ESSM allowed				0.11								
9. DDG SM-2 allowed												
10. DDG ESSM allowed				0.17								
Uncontrollable factors or Unknown information												
11. SM-2 p_hit												
12. ESSM p_hit												
13. RAM p_hit												
14. HF p_hit												
15. Spike p_hit												
16. APKWS p_hit												
17. TUAV det ratio												
18. LCS det ratio												
19. En boat det ratio							0.04					
20. USV det ratio												
21. TUAV class rng												
22. LCS class rng												
23. En boat class rng					- 0.03						0.02	
24. USV class rng												
25. En boat multiplier	0.20	0.05						0.02				

The following observations can be made about the results in Table 11:

1. Factor 1 is most influential on all MOPs except for MOPs 3 and 7.
2. Factor 3 has moderate influence on MOPs 7, 8, and 10, as well as weak influence on MOP 6.
3. Factor 4 has moderate influence on MOPs 6 and 7, as well as weak influence on MOP 11.
4. Factor 6 has moderate influence on MOP 5.
5. Factor 7 has moderate influence on MOPs 3 and 11.
6. Factors 8 and 10 have moderate influence on MOP 4.

7. Factor 19 has weak influence on MOP 7.

8. Factor 23 has weak influence on MOPs 5 and 11.

9. Factor 25 has moderate influence on MOP 1, as well as weak influence on MOPs 2 and 8.

10. Factors 2, 5, 9, 11 to 18, 20 to 22, and 24 do not appear as influential factors.

Key insights are gained from these observations:

1. The number of LCSs (factor 1) is highly significant in influencing all three MOEs (observation 1). This is likely due to the LCS, with longer range and more missiles, being more efficient at killing enemy boats, as compared to the armed TUAV or USV. Killing more enemy boats before they can launch the C704 missiles results in fewer C704 missiles being fired and thereby less SM-2, ESSM, and RAM (MOPs 3 to 5) being used against the incoming C704 missiles. Using fewer SM-2, ESSM, and RAM generally results in a lower cost of weapons expended (MOP 11), given that the SM-2, ESSM, and RAM are more costly than the Hellfire, Spike, and APKWS weapons used against enemy boats (reference Table 6).

2. The number of TUAVs carried per LCS (factor 3) is significant (observation 2) but not as significant as the number of LCSs, in influencing the proportion of Hellfire used, proportion of Spike used, and TUAV fuel used. This could be due to fewer APKWS missiles carried per TUAV and the shorter range of the APKWS missile. In comparison, there are more Hellfire missiles carried per LCS, and the Hellfire missile range is longer than the range of the APKWS.

3. The number of USVs (factor 2) is not shown to be significant (observation 10). This could be due to the small number of USVs (up to five) and that each USV carries only two Spike missiles.

4. Arming the TUAV (factor 4) helps reduce the proportion of Hellfire and Spike missiles used, and results in a lower cost of total weapons expended (observation 3).

5. The uncontrollable factors (11 to 25) do not stand out in influencing the MOPs (observations 7 to 10). They are mostly not significant, with only five occurrences of weak influence and one occurrence of moderate influence. This means that the capability portfolio options, generated from varying factors 1 to 4, are fairly robust across the variety of weapon and sensor performances as well as number of enemy boats.

6. A policy for limiting the number of SAMs used does not show up as an influential factor on the C704 and boat leakers (observations 1 and 2). This, coupled with the insight that allowing fewer SAMs to be used results in a lower proportion of the particular SAM being used (observations 4 to 6), means that there is a possible space to limit and conserve SAM use (CG SM-2, CG ESSM, DDG ESSM, and CVN RAM, specifically) without resulting in increasing C704 and boat leakers.

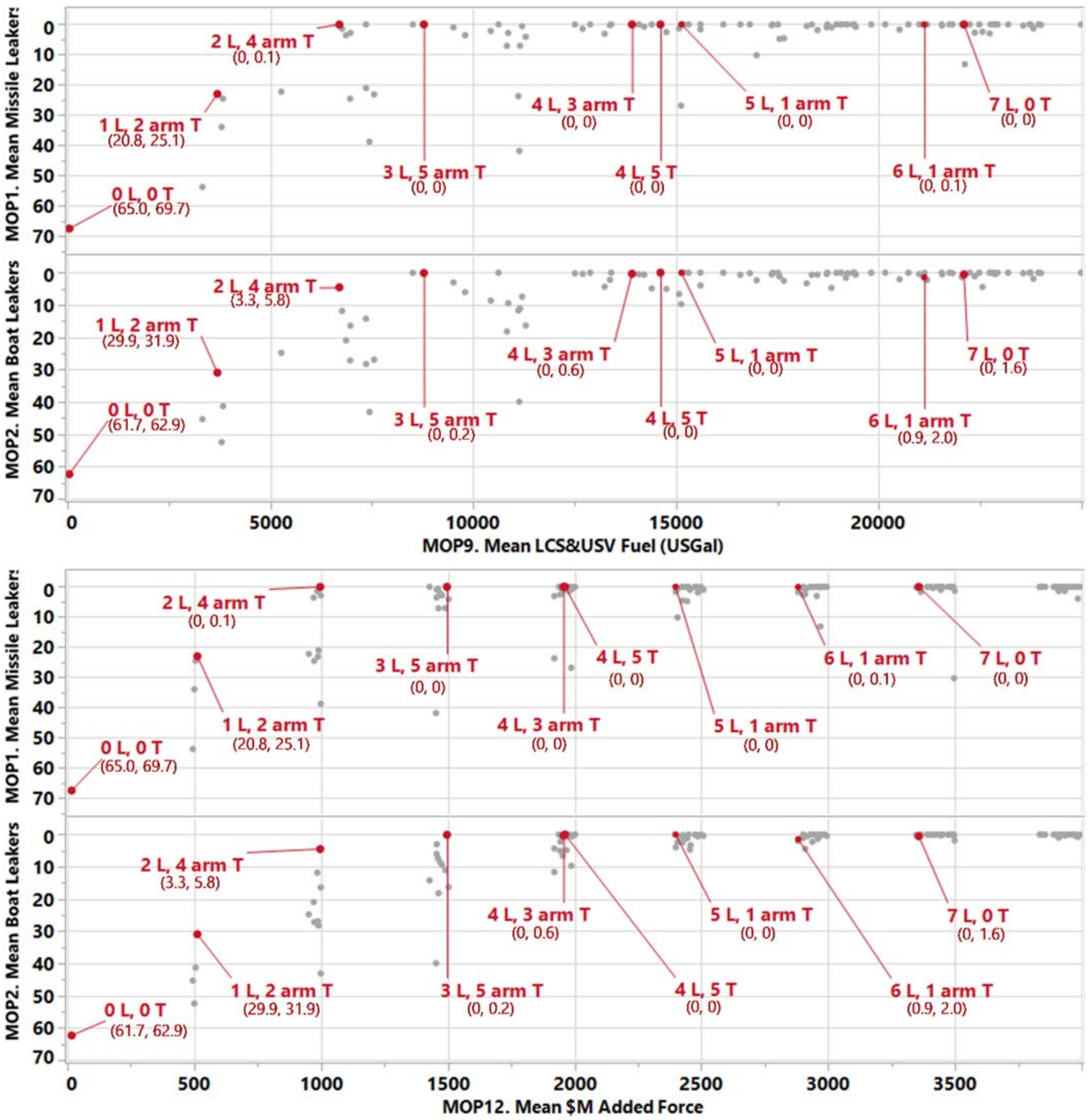
The other insights are:

1. Allowing more SM-2 to be used results in a higher cost of weapons expended (observation 5).
2. Having more LCSs or TUAVs results in a larger denominator of weapon stock, and thereby a lower proportion of the respective weapon being used (observations 1 and 2).
3. The number of TUAVs, a function of the number of LCSs and the TUAV-LCS multiplier, significantly influences TUAV fuel used (observations 1 and 3).
4. The number of LCSs significantly influences the LCS and USV fuel used, as well as the costs of weapons and added force (observation 1). This is due to the LCS being the greatest driver of diesel fuel consumption (reference Table 5) and platform cost (reference Table 6).
5. More enemy boats would require more weapons to be used and increase the number of enemy missiles that could be launched, thereby increasing the chance of closing on the CVN (observation 9).
6. Shorter enemy boat classification ranges means more enemy missiles are launched at closer ranges, resulting in slightly heavier use of the mid-range ESSM and higher weapons cost (observation 8).
7. Longer enemy boat detection ranges means detecting unknown targets further and investigating them earlier. This could have resulted in more use of the Spike missiles (observation 7).

Preliminary PEF curves for mean missile leakers (MOP 1) and mean boat leakers (MOP 2) versus mean LCS and USV fuel used (MOP 9) and mean cost of added force (MOP 10) were plotted in Figure 8, assuming these were MOPs important to a decision maker. These MOPs were chosen to examine the efficient options in terms of force protection effectiveness, fuel consumption, and cost.

The PEF findings should be treated as preliminary. A study using a higher-resolution model would be the next step. The nearly orthogonal property of the NOB design resulted in dissimilar sets of values for non-force configuration factors (such as SAM use limits, weapon hit probabilities, sensor ranges and enemy boat multiplier). This did not enable a complete like-for-like comparison between each force configuration option. The tabulate tool in JMP is a simplistic method used to generate a new set of mean MOP values mapped to each force configuration option. This was done by averaging the mean MOP results, grouped by the number of LCSs, number of TUAVs and TUAV armed-or-not. The number of USVs was not included as it was not identified as an influential factor. The number of TUAVs was obtained from the product of the TUAV multiplier and the number of LCSs rounded up to an integer. Selected data points that lay close to or on the PEF curve were labeled with the respective force configuration and 95 percent confidence interval. A 95 percent confidence interval was a range of values where there was a 0.95 probability that the actual mean lay within the range. The idealized PEF curves were not plotted.

The instances in which the number of missile and boat leakers were close to zero (≤ 0.5) occurred when there were three or more LCSs. A closer look at the data in JMP reveals three LCSs with five to six TUAVs to be the lowest cost and fuel consumed options. The horizontal portion of the four PEF curves show that fewer armed TUAVs are needed as the LCSs increased from three to six. At seven LCSs or more, it is possible to dispense with deploying TUAVs. At four LCSs or more, it is also possible to rely on a mix of LCSs and only unarmed TUAVs to attain close to zero leakers.



Note: The 95% confidence intervals for the mean MOPs 1 and 2 values are in parentheses.

Figure 8. Experiment One—Preliminary PEF Curves.

The tradeoffs between force protection, weapon and fuel consumption, and costs are examined for the option of three LCSs with five to six armed TUAVs, assuming this was an optimal force configuration. Figure 9 is a JMP parallel plot of the MOP results for three LCSs with five to six TUAVs versus all other possible options. Each column has a y-axis in the different units of measure for the specified MOP. The horizontal lines

represent the different force configurations. Each line then, traces that specific force configuration's performance in terms of each MOP. Data labels for MOPs 6 to 8 are not included as it is not meaningful to expect less use of these weapons that traded for less use of the SM-2, ESSM, and RAM.

There are important results presented in Figure 9. The red line is the baseline case with zero LCSs and TUAVs, with data values for the specific MOPs in red. The blue lines are the MOP results for three LCSs with five to six TUAVs, with data values for the specific MOPs in blue. The figure shows the increases from zero to 8800 U.S. Gal in diesel fuel consumed (MOP 9), from 0 to 800 lbs in aviation fuel consumed (MOP 10), and from 0 to $1500M in cost of added force (MOP 12). The resulting performance gains are the 100 percent decrease in missile leakers (MOP 1), 99.8 percent decrease in boat leakers (MOP 2), 23 percent decrease in use of SM-2 (MOP 3), 35 percent decrease in use of ESSM, 49.4 percent decrease in use of RAM (MOP 5), and 61.5 percent decrease in cost of weapons expended (MOP 11).

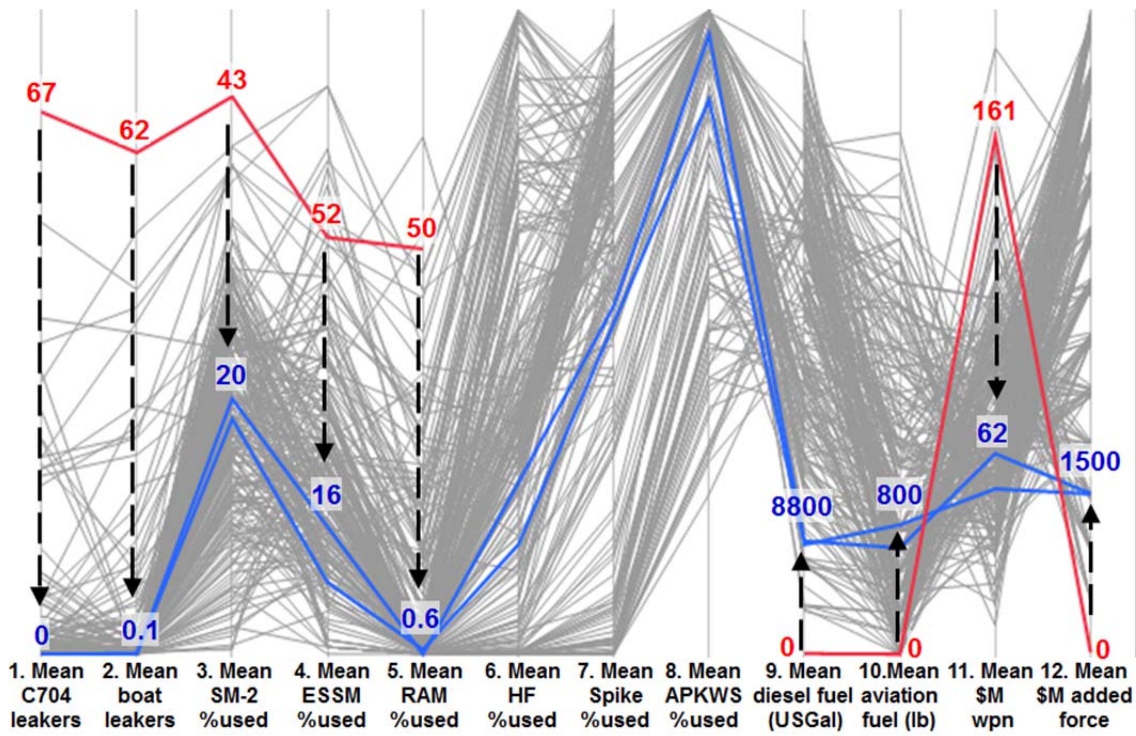


Figure 9. Experiment One—Tradeoffs for Three LCSs with Five to Six Armed TUAVs.

G. IMPETUS FOR EXPERIMENT TWO

In the first experiment, setting the data filter in JMP to have at least 70 percent of SAMs available for use in factors 5 to 10 filtered out all design points except for two. This means that insights are limited on the impact of varying other factors when not limiting any use of the SAMs. To derive a good set of insights in this part of the experimental space, another experiment was conducted with factors 5 to 10 set at their baseline values. The remaining nineteen factors were unchanged. The 512-design point NOB design was used with the baseline case added as the 513th design point. The largest pairwise correlation has a magnitude of 0.0261, showing that the design preserves its nearly orthogonal property.

H. RESULTS OF EXPERIMENT TWO

The R^2 contributions from the significant factors in the second experiment are in Table 12. The legend is the same as for Table 11.

Table 12. Experiment Two—Influential Factors and R^2 Contributions.

Experiment #2	MOP											
	1. mean c704 leakers	2. mean boat leakers	3. mean SM-2 %used	4. mean ESSM %used	5. mean RAM %used	6. mean Hellfire %used	7. mean Spike %used	8. mean APKWS %used	9. mean LCS & USV fuel used	10. mean TUAV fuel used	11. mean $M wpns used	12. mean $M added force
Controllable factors												
1. #LCS	- 0.32	- 0.72	- 0.50	- 0.70	- 0.45	- 0.56	- 0.29	- 0.37	0.77	0.40	- 0.69	0.96
2. #USV												
3. #TUAV/LCS						- 0.06	- 0.09	- 0.30		0.38		
4. TUAV armed?						- 0.15	- 0.22				- 0.01	
Uncontrollable factors or Unknown information												
5. SM-2 p_hit												
6. ESSM p_hit												
7. RAM p_hit												
8. HF p_hit												
9. Spike p_hit												
10. APKWS p_hit												
11. TUAV det ratio												
12. LCS det ratio												
13. En boat det ratio		- 0.02	- 0.01	- 0.05	- 0.01						- 0.04	
14. USV det ratio												
15. TUAV class rng												
16. LCS class rng												
17. En boat class rng			0.02		- 0.26							
18. USV class rng												
19. En boat multiplier		0.05						0.02				

The following observations can be made about the results in Table 12:

1. Factor 1 is most influential on all MOPs.
2. Factor 3 has moderate influence on MOPs 8 and 10, as well as weak influence on MOPs 6 and 7.
3. Factor 4 has moderate influence on MOPs 6 and 7, as well as weak influence on MOP 11.
4. Factor 13 has weak influence on MOPs 2 to 5, and 11.
5. Factor 17 has moderate influence on MOP 5 and weak influence on MOP 3.
6. Factor 19 has weak influence on MOPs 2 and 8.
7. Factors 2, 5 to 12, 14 to 16, and 18 do not appear as influential factors.

Similar key insights are gained from the observations about the second experiment, and reinforce the key insights from the first experiment:

1. The number of LCSs (factor 1) is highly significant in influencing all three MOEs (observation 1).

2. The number of TUAVs carried per LCS (factor 3) is a significant influential factor (observation 3) but not as significant as the number of LCSs.

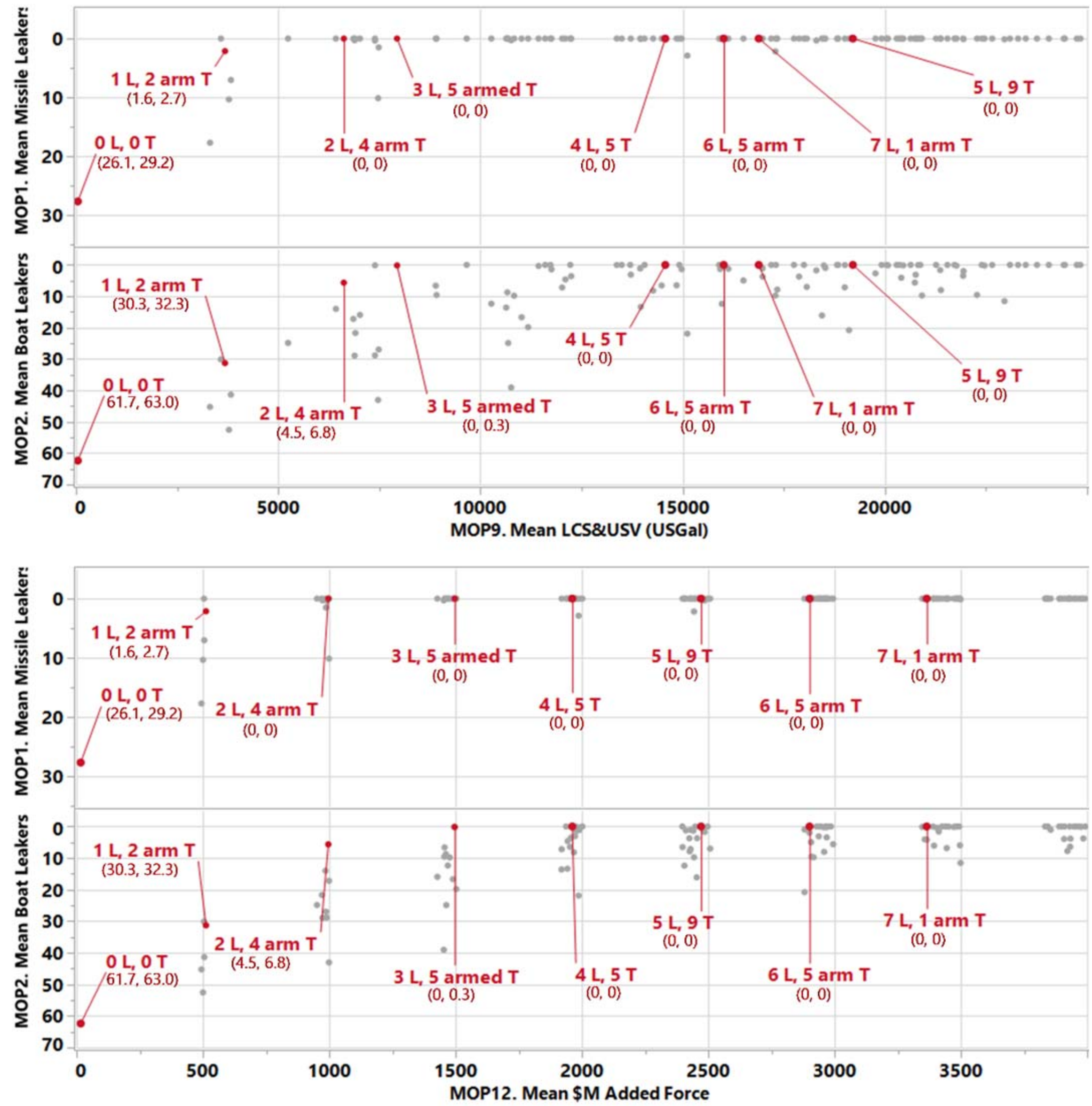
3. The number of USVs (factor 2) is not significant (observation 7).

4. Arming the TUAVs (factor 4) helps reduce the proportion of Hellfire and Spike missiles used, and results in a lower cost of weapon expenditure (observation 3).

There is a new minor insight observed from the second experiment:

- Longer enemy boat detection ranges mean more boat leakers, greater proportion of SAMs used, and lower cost of weapons expended (observation 4). This makes sense as the enemy boats would detect the CVN earlier, and thereby speed up to investigate the CVN earlier. The impact of lower weapons cost is possibly due to more enemy boats being destroyed as a consequence of detecting and investigating the LCSs or USVs earlier.

The preliminary PEF curves for the second experiment are in Figure 10. The axes, legend, and tabulation are the same as for Figure 8. The same caution to follow up on these findings by running experiments with a higher-resolution model applies. It is similarly observed that for the configurations of three or more LCSs, close to zero (≤ 0.5) missile and boat leakers occurred. A closer look at the data in JMP reveals three LCSs, each carrying five to six TUAVs, to be the lowest cost and fuel consumed options. Looking at the horizontal portion of the four PEF curves, fewer armed TUAVs are needed as the LCS increases beyond six. This time, it is possible to dispense with deploying TUAVs at nine LCSs or more (data point not shown on chart). At four LCSs or more, it is possible to rely on a mix of LCSs and only unarmed TUAVs to attain close to zero leakers. The PEF findings are largely consistent with the first experiment.



Note: The 95% confidence intervals for the mean MOPs 1 and 2 values are in parentheses.

Figure 10. Experiment Two—Preliminary PEF Curves.

The tradeoffs between force protection, weapon and fuel consumption, and costs are again examined for the option of three LCSs with five to six armed TUAVs. Figure 11 shows the increases from 0 to 8800 U.S. Gal in diesel fuel consumed (MOP 9), from 0 to 800 lbs in aviation fuel consumed (MOP 10), and from 0 to $1500M in cost of added force (MOP 12). The resulting performance gains are the 100 percent decrease in mean

missile leakers (MOP 1), 99.8 percent decrease in mean boat leakers (MOP 2), 25 percent decrease in SM-2 used (MOP 3), 71 percent decrease in ESSM used (MOP 4), 70.8 percent decrease in RAM used (MOP 5), and 59 percent decrease in cost of weapons expended (MOP 11). The legend is the same as for Figure 9. The tradeoffs are similar to that in the first experiment. The MOP data values should not be quantitatively compared with the first experiment due to the dissimilar spread of other factor values (such as weapon hit probabilities and sensor ranges).

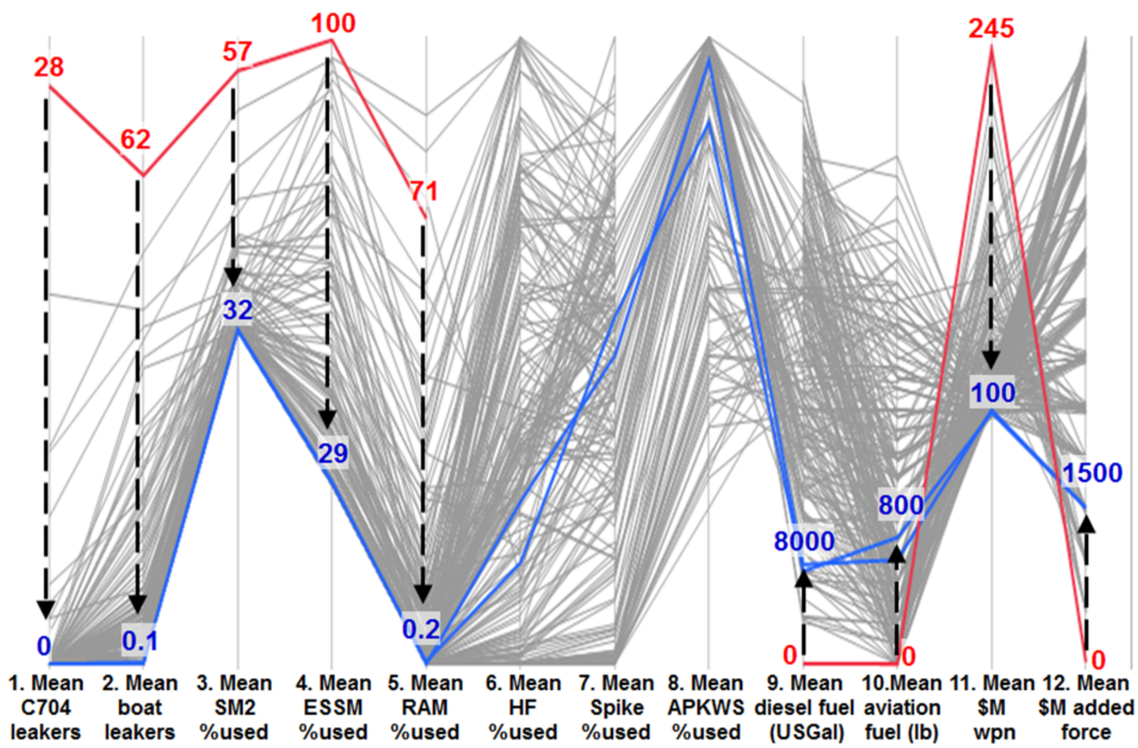


Figure 11. Experiment Two—Tradeoffs for Three LCSs with Five to Six Armed TUAVs.

As a quick summary, the findings on the significant influential factors and optimal force configurations in the second experiment appear consistent with those in the first experiment, despite the removal of limits on SAMs use in the second experiment.

I. IMPOSING LIMITS ON MOP RESULTS

Hypothetical limits on important MOPs, such as leakers, fuel consumption, and costs, can be imposed to identify force configurations that meet these limits. An example building on data from Figure 11 is shown. We seek to identify force options that meet the following example limits: the mean number of missile leakers (MOP 1) and boat leakers (MOP 2) have to be less than 0.5 leakers each; the diesel fuel consumed (MOP 9), aviation fuel consumed (MOP 10), cost of weapons expended (MOP 11), and cost of added force (MOP 12) cannot exceed the midpoint of the range of values. The data filter in JMP is used to identify the horizontal lines (denoted in blue) that meet the imposed limits. For follow-on studies, both absolute and percentage values can be used in setting such limits.

Figure 12 shows that reducing missile leakers (MOP 1) increases the minimum number of LCSs needed. At least one LCS is needed when limiting missile leakers to be less than 0.5.

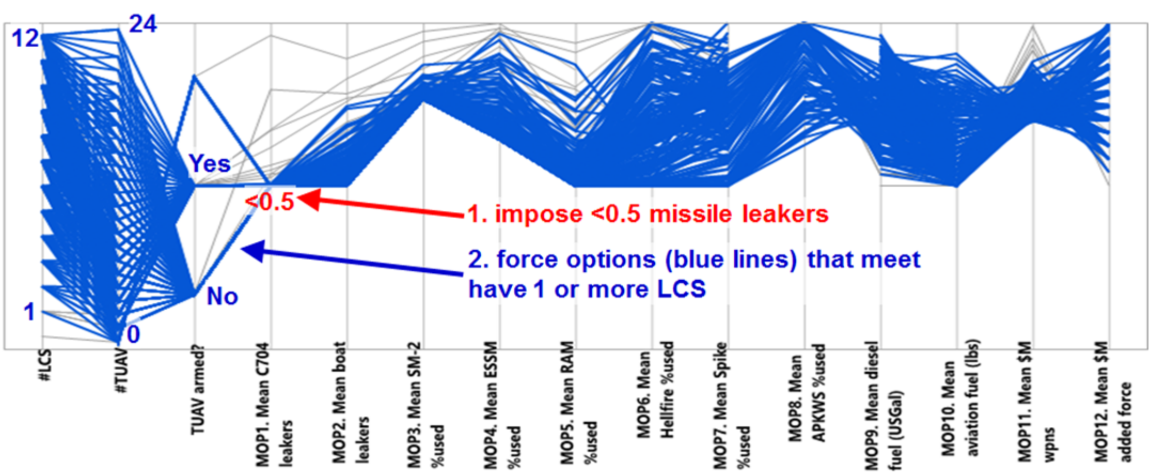


Figure 12. Impact of Imposing ≤0.5 Limit on Mean Missile Leakers (MOP 1).

Figure 13 shows that reducing boat leakers (MOP 2) increases the minimum number of LCSs needed. At least three LCSs are needed when limiting the average number of boat leakers to be less than 0.5. Achieving close to zero boat leakers appears

more stringent and requires more LCSs, as compared to achieving close to zero missile leakers.

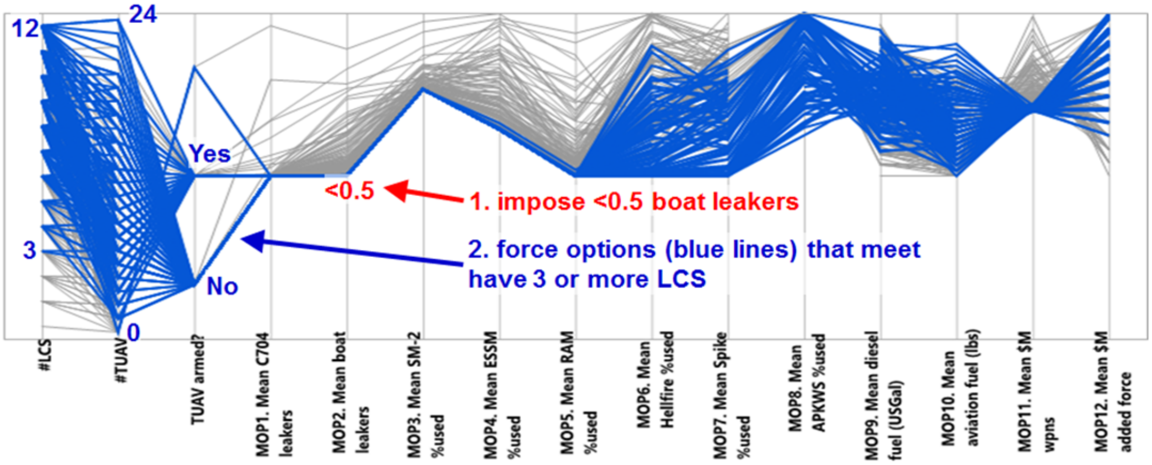


Figure 13. Impact of Imposing ≤0.5 Limit on Mean Boat Leakers (MOP 2).

Figure 14 shows that limiting diesel fuel consumed (MOP 9) reduces the maximum number of LCSs and TUAVs that can be deployed. The largest force configurations have at most ten LCSs (with six TUAVs), and at most seventeen TUAVs (with nine LCSs), when limiting diesel fuel consumed to the midpoint of the range of values.

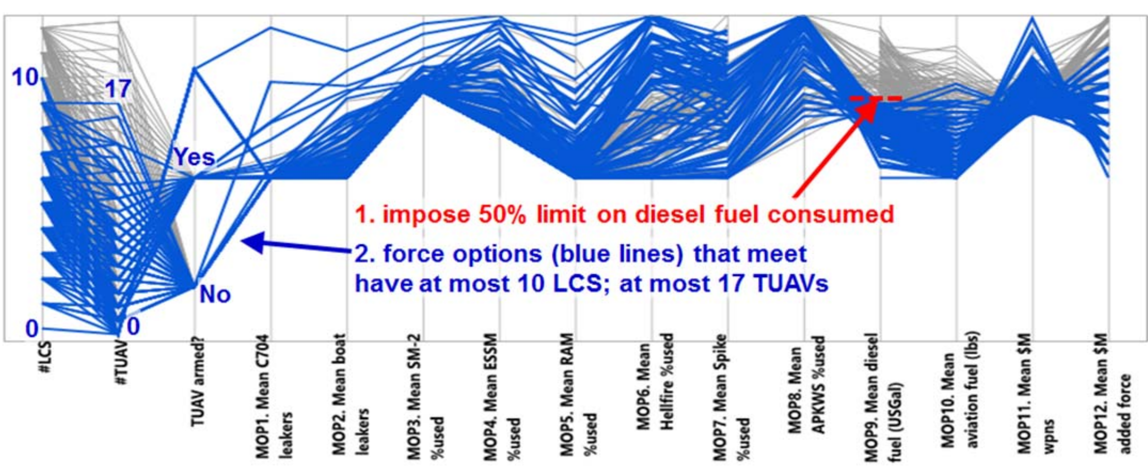


Figure 14. Impact of Imposing 50% Limit on Mean Diesel Consumed (MOP 9).

Figure 15 shows that limiting aviation fuel consumed (MOP 10) reduces the maximum number of TUAVs that can be deployed. There can be at most twelve TUAVs when limiting aviation fuel consumed to the midpoint of the range of values.

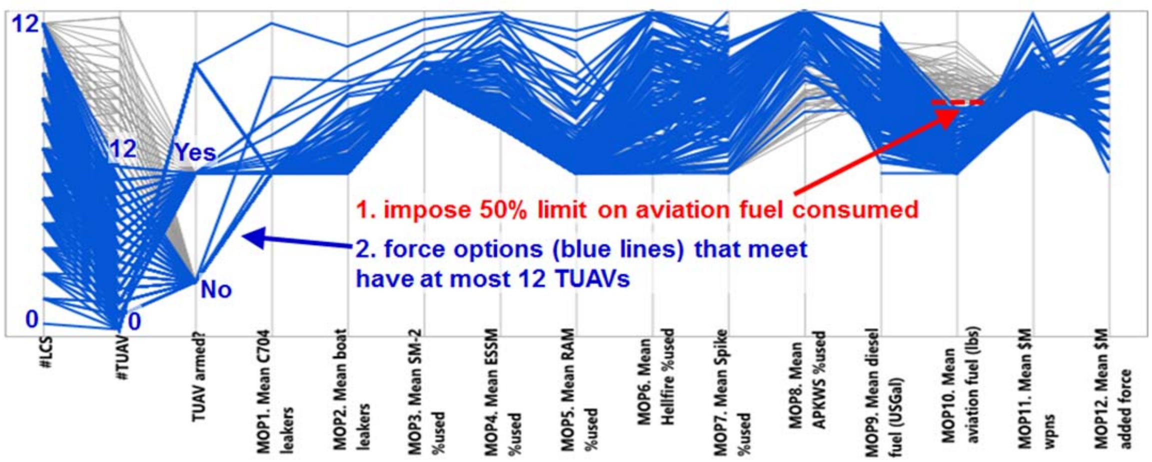


Figure 15. Impact of Imposing 50% Limit on Mean Aviation Fuel Consumed (MOP 10).

Figure 16 shows that limiting cost of weapons expended (MOP 11) increases the minimum number of LCSs needed. At least one LCS is needed when limiting cost of weapons to the midpoint of the range of values.

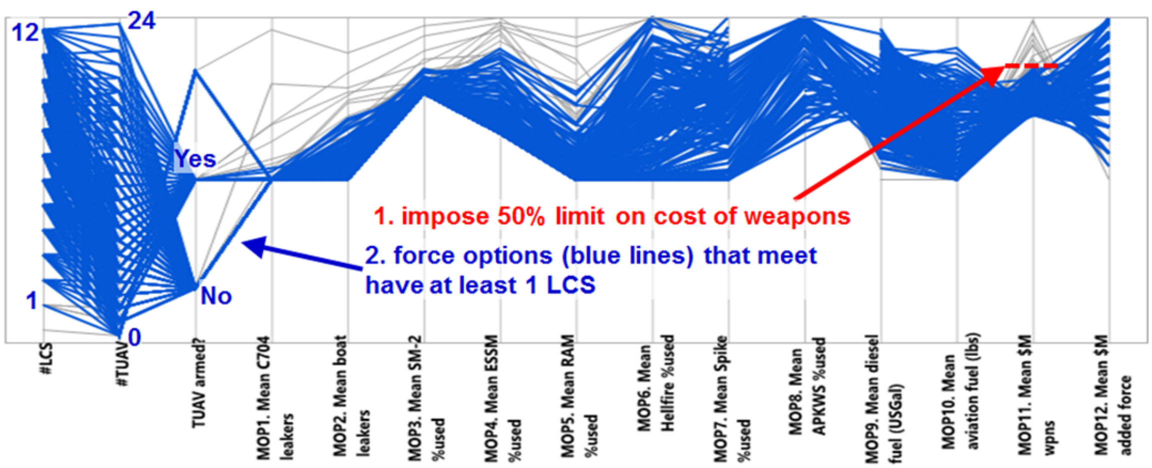


Figure 16. Impact of Imposing 50% Limit on Mean Cost of Weapons Expended (MOP 11).

Figure 17 shows that limiting cost of added force (MOP 12) reduces the maximum number of LCSs and number of TUAVs that can be deployed. There can be at most six LCSs, with at most twelve TUAVs, when limiting cost of added force to the midpoint of the range of values.

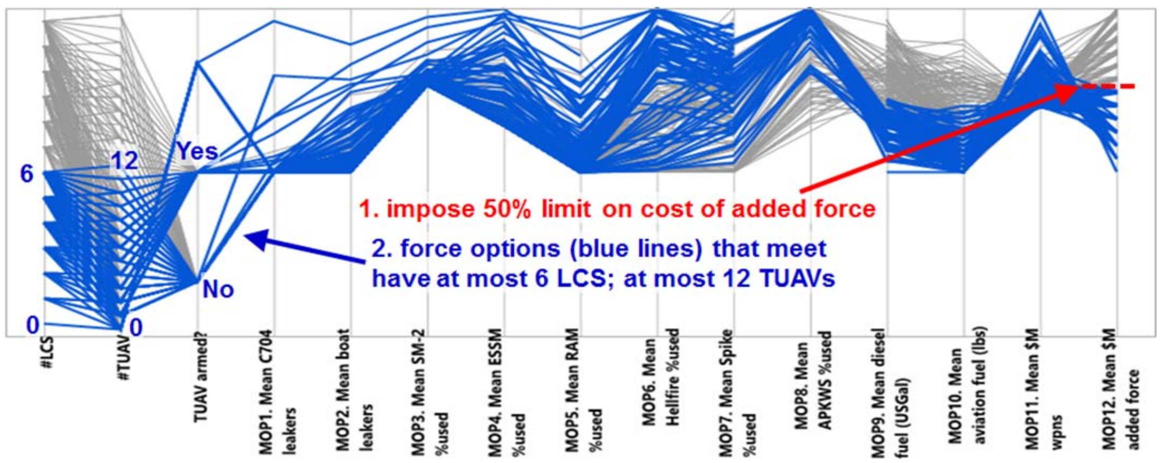


Figure 17. Impact of Imposing 50% Limit on Mean Cost of Added Force (MOP 12).

Figure 18 shows the overall impact when combining all imposed limits. The force options are limited to three to six LCSs and one to eleven TUAVs. This first cut of three to six LCSs, each carrying one to eleven TUAVs, should be followed by a higher-resolution study for refinement and verification.

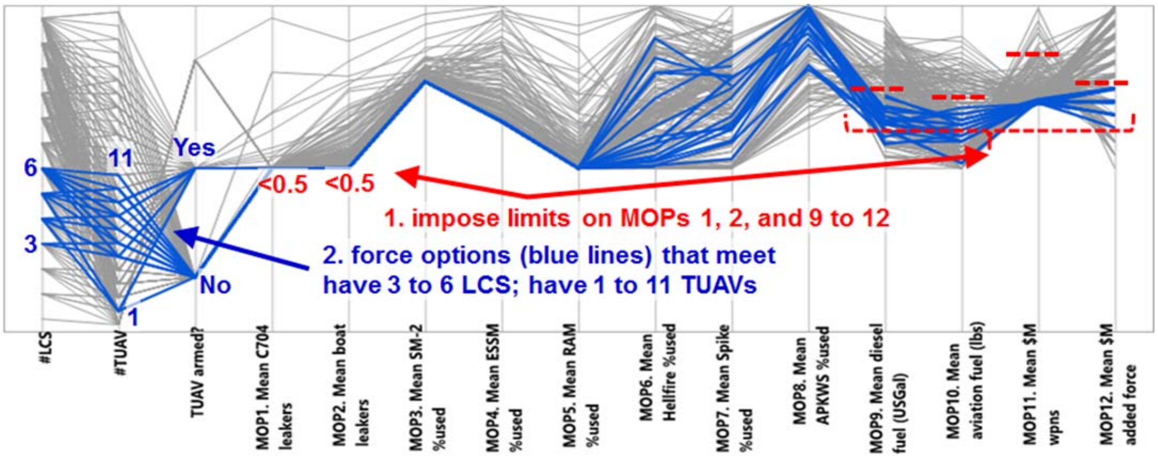


Figure 18. Overall Impact of Imposing Limits.

The analysis of MOPs in this thesis considers only the mean values. Decision makers may also be interested in other summary measures. For example, they may be concerned about making sure that there are no missile and boat leakers 90 percent of the time. Such an analysis will involve filtering of the data in JMP in a different manner.

J. IMPETUS FOR EXPERIMENT THREE

Having built a simulation model that worked fairly well, we conducted a third experiment to garner insights, if any, on possible "low hanging fruit" research and development (R&D) options that can reap significant gains in any performance measure. These options, which require minimal R&D effort for maturation, involve scaling the level of current technology or retrofitting existing technology onto a building block capability. The notional set of near-term options include:

1. Duplicating the existing SSMM load (24 shot) of Hellfire missiles onboard the LCS to have a total of 48 Hellfire missiles, with the assumption that the payload can still fit onboard the LCS.

2. Equipping the TUAV with a larger capacity APKWS-launcher, such as the 19-shot digital rocket launcher found on the MH-60 (IHS 2014c). The Fire Scout MQ-8B, if not the more advanced MQ-8C, is assumed to be able to carry the payload.

3. This is assumed to be within the payload capacity of

4. Equipping the USV with more Spike missiles, such as through the installation of a quadruple launcher (Rafael 2010) or octuple launcher

(Eshel 2013). It is assumed that these launchers can be integrated into the 11 m USV.

5. Equipping the USV with the Spike ER missile that has a longer range of 8 km (IHS 2015h), as compared to the Spike LR missile with a range of 4 km. It is assumed that the Spike ER can be integrated into the 11 m USV.

6. Expanding the number of USVs that can be operated autonomously from the existing five, by scaling the level of autonomous technology.

Another key objective for the third experiment is to investigate whether decoupling the number of TUAVs from being a multiplier of the number of LCSs would make the former show up as a more influential factor. Operationally, this means that there can be more TUAVs than could be carried onboard the LCS ships. For such cases, ships other than the LCSs are needed to deploy the TUAVs. The 512-design point NOB design is used again with the baseline case as the 513th design point. The largest pairwise correlation still has a magnitude of 0.0261, which shows the nearly orthogonal property of the experimental design.

Building on the factors used in the second experiment, the factor on the number of USVs is amended to have a high limit of 24 USVs while four new factors are added. The factor on the TUAV-LCS multiplier is changed to the number of TUAVs with a high limit of 24. The changes are in Table 13. A total of 23 factors are investigated in this experiment.

Table 13. Testing Near-Term R&D Options and Decoupling Number of TUAVs from Number of LCSs.

Objective	Factor	Low Limit	High Limit	Remarks
Investigate near-term R&D options	#Hellfire per LCS	24	48	
	#APKW per TUAV	8	38	
	#Spike per USV	2	8	
	Spike range	4000	8000	In meters
	#USV	0	24	
Investigate standalone #TUAV numbers	#TUAV	0	24	Replaces TUAV-LCS multiplier factor

K. RESULTS OF EXPERIMENT THREE

The R^2 contributions from the significant factors in the third experiment are in Table 14. The use of color banding and minus sign is same as in Table 11. The R&D-related and number of TUAV factors being investigated are highlighted in yellow and light blue, respectively.

Table 14. Experiment Three—Influential Factors and R^2 Contributions.

Experiment #3	1. mean c704 leakers	2. mean boat leakers	3. mean SM-2 %used	4. mean ESSM %used	5. mean RAM %used	6. mean Hellfire %used	7. mean Spike %used	8. mean APKWS %used	9. mean LCS & USV fuel used	10. mean TUAV fuel used	11. mean $M wpns used	12. mean $M added force
Controllable factors												
1. #LCS	- 0.07	- 0.24	- 0.12	- 0.19	- 0.20	- 0.29			0.76		- 0.16	0.96
2. #TUAV						- 0.04	- 0.13	- 0.72		0.95		
3. TUAV armed?		- 0.18		- 0.13	- 0.02	- 0.36	- 0.54		- 0.09		- 0.07	
4. #USV	- 0.19											
5. #APKWS/TUAV								- 0.10				
6. #HF/LCS												
7. #Spike/USV												
8. Spike LR or ER												
Uncontrollable factors or Unknown information												
9. SM-2 p_hit												
10. ESSM p_hit												
11. RAM p_hit												
12. HF p_hit												
13. Spike p_hit												
14. APKWS p_hit	- 0.02		- 0.02									
15. TUAV det ratio												
16. LCS det ratio												
17. en boat det ratio		- 0.07	- 0.09	- 0.14							- 0.11	
18. USV det ratio												
19. TUAV class rng												
20. LCS class rng												
21. en boat class rng			0.01									
22. USV class rng												
23. en boat multiplier												

The following observations can be made about the results in Table 14:

1. Factor 1 is most influential on MOPs 2 to 5, 9, 11, and 12. It has moderate influence on MOP 6 and weak influence on MOP 1.

2. Factor 2 is most influential on MOPs 8 and 10. It has moderate influence on MOP 7 and weak influence on MOP 6.

3. Factor 3 is most influential on MOPs 6 and 7. It has moderate influence on MOPs 2 and 4, as well as weak influence on MOPs 5, 9, and 11.

4. Factor 4 is most influential on MOP 1.

5. Factor 5 has moderate influence on MOP 8.

6. Factor 14 has weak influence on MOPs 1 and 3.

7. Factor 17 has moderate influence on MOPs 4 and 11, as well as weak influence on MOPs 2 and 3.

8. Factor 21 has weak influence on MOP 3.

9. Factors 6 to 13, 15, 16, 18 to 20, 22, and 23 do not appear as influential factors.

Key insights are gained from the observations:

1. Increasing the number of USVs has moderate influence on reducing missile leakers (observation 4). Increasing APKWS missiles per TUAV has weak influence (observation 5) on reducing the proportion of APKWS missiles used—due to having more missiles vs. a same number of enemies. Increasing Hellfire missiles per LCS (factor 6), Spike missiles per USV (factor 7), and longer range Spike missile (factor 8) are not influential (observation 9). These, along with increasing APKWS missiles per TUAV, do not appear as useful near-term R&D options.

2. The number of TUAVs has become more influential on MOPs 8 and 10 (observation 2), as compared with the first two experiments. This is not surprising as the (standalone) number of TUAVs is the key driver of APKWS missiles being carried, when armed, and TUAV fuel consumed.

3. The number of USVs has become more influential on MOP 1 (observation 4), as compared with the first two experiments. This is likely due to the scaling of up to 24 USVs that distract the enemy boats from approaching and launching missiles at the CVN.

4. The number of LCSs continues to be most influential across most of the MOPs (observation 1). There is some consistency with the findings from the first two experiments on the dominant influence of this factor.

5. On MOP 1, the number of LCSs does not appear as the most influential factor, while the number of USVs appears as having moderate influence. This is likely due to the number of USVs playing a bigger role (deployed ahead of the LCSs) against the enemy boats now that it is scaled up to 24 USVs.

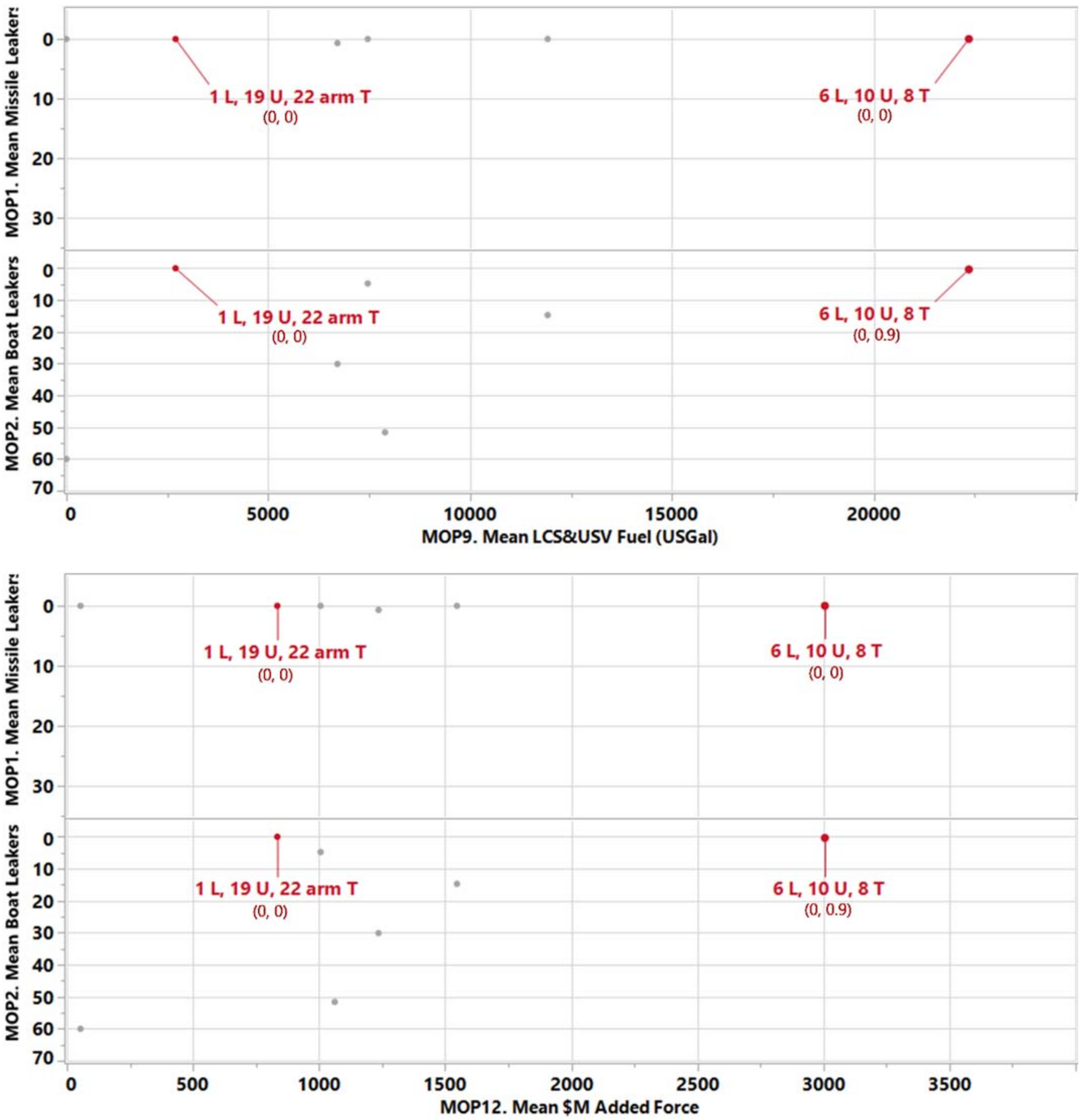
There is a new minor insight:

- A higher probability of hit for the APKWS leads to slightly fewer missile leakers and a slightly lower proportion of SM-2 used (observation 6).

More enemy boats being killed by more accurate APKWS missiles means fewer C704 missiles that could be launched.

Overall, except for scaling up the number of USVs, the suggested near-term R&D options do not appear to improve MOP behaviors. Resources should be invested in more significant factors such as the number of LCSs and arming the TUAVs—both have moderate influence on reducing boat leakers and proportion of SAMs used.

In plotting the preliminary PEF curve, all except three of the 513 design points have accounted for some form of R&D. If the scaling of the number of USVs is included, since this R&D option shows a moderate influence on MOP 1, an incomplete curve with seven data points can be plotted and is shown in Figure 19. The axes and legend are the same as for Figure 8. The tabulation done in JMP, this time, is grouped by the number of LCSs, number of USVs, number of TUAVs, and TUAV armed-or-not. A key qualitative insight from Figure 19 is that close to zero (<0.5) missile and boat leakers are achievable at a lower cost (about $850M onwards), as compared to about $1500M onwards in both Figures 8 and 10. This is likely due to having fewer than three LCSs, along with the scaling up of the number of USVs, the number of TUAVs, or both.



Note: The 95% confidence intervals for the mean MOPs 1 and 2 values are in parentheses.

Figure 19. Experiment Three—Preliminary Efficiency Frontier Curves (includes R&D Scaling of USV Numbers).

L. IMPETUS AND RESULTS OF EXPERIMENT FOUR

As the cost-effective or fuel-efficient force options for any mix of LCSs, USVs, and TUAVs might interest decision makers, a fourth experiment was conducted to complete the left portion of the PEF curves in Figure 19. This experiment assumes that up

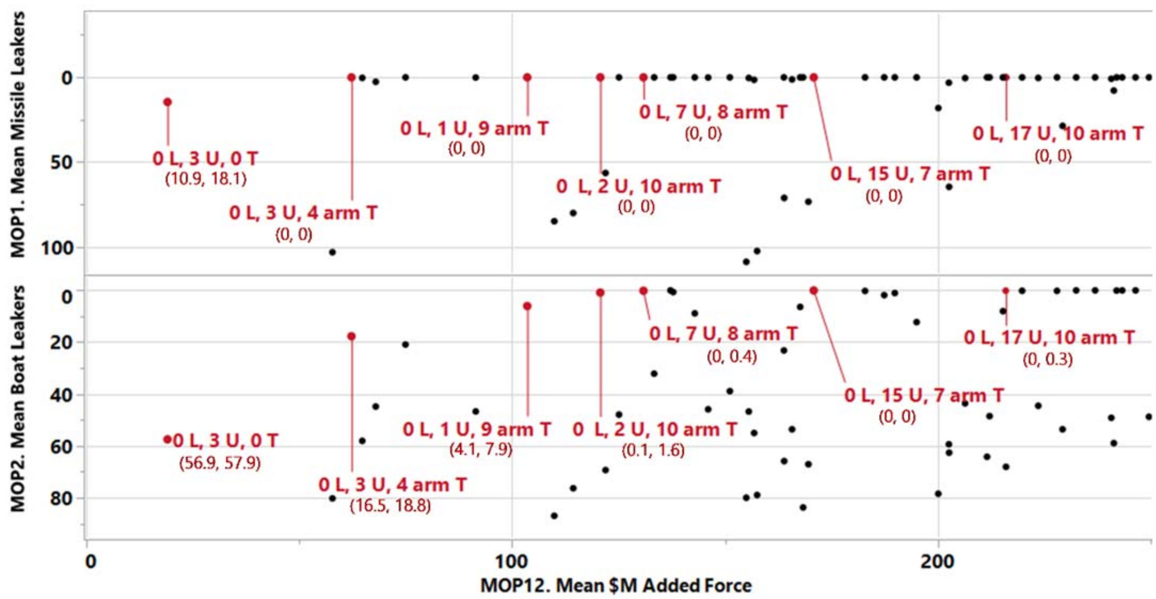
to 24 autonomous USVs and up to 24 TUAVs (regardless of the number of LCSs) can be operated. The set of factors used is the same as in the second experiment except for the changes shown in Table 15. The largest pairwise correlation still has a magnitude of 0.0261, showing the nearly orthogonal property of the experimental design.

Table 15. Factor Changes for Experiment Four.

Factor	Low Limit	High Limit	Remarks
#LCSs	0	6	High limit reduced to 6 to create more data points on left portion of PEF curves
#USVs	0	24	Assume R&D scaling of up to 24 autonomous USVs
#TUAVs	0	24	Assume standalone TUAV numbers; replaced TUAV-LCS multiplier factor

The preliminary PEF curves for the fourth experiment are shown in Figure 20. The legend and tabulation are the same as for Figure 19 except that MOPs 1 and 2 are plotted only against MOP 12. It is not useful to plot against MOPs 9 or 10 as options that can have zero LCSs, USVs, or TUAVs can appear. This can result in zero additional diesel or aviation fuel used from the portfolio baseline, and will clutter the vertical axes. The same caution to follow the preliminary curves with a higher-resolution model applies.

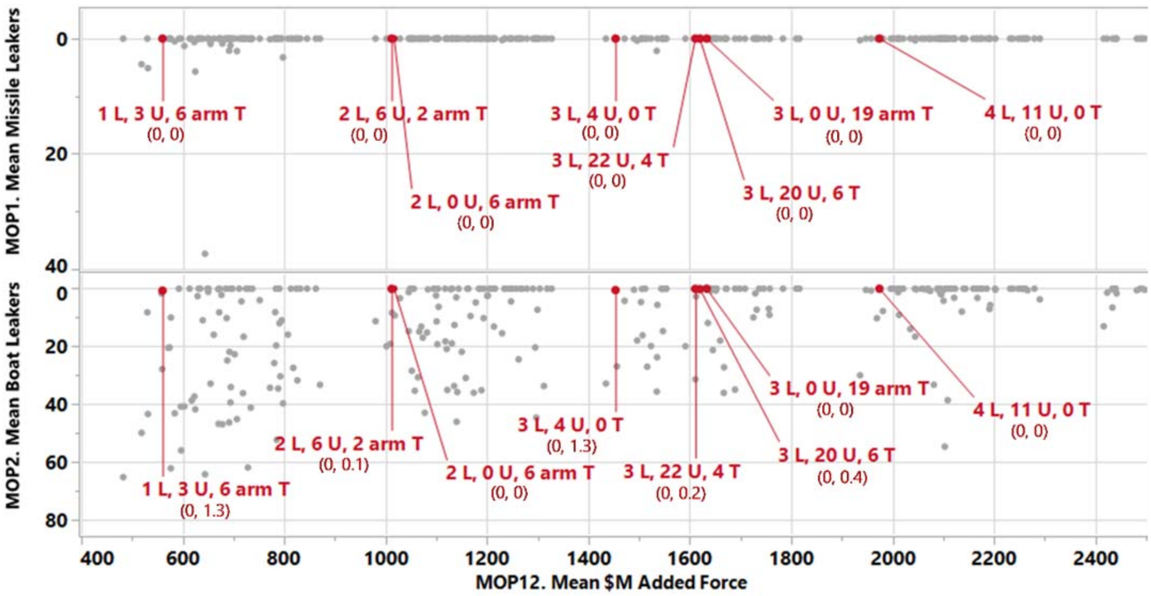
With the number of USVs scaled up and the deployment of TUAVs unhinged from the number of LCSs, new cost-effective force options have appeared, as compared with the first three experiments. The added force costs of these options, however, have not incorporated the cost of additional TUAV deployment platforms added to the portfolio baseline. Close to zero (≤ 0.5) missile and boat leakers occurred, at an added force cost of $130M and upwards, for configurations such as 0 LCSs/7 USVs/8 armed TUAVs, 0 LCSs/15 USVs/7 armed TUAVs, and 0 LCSs/17 USVs/10 arm TUAVs. Within the cost range of up to $250M, force configurations that attained close to zero leakers did not have the LCSs or unarmed TUAVs. A search of the entire set of results in JMP also did not reveal any USV-only or TUAV-only force configurations that attained close to zero leakers.



Note: The 95% confidence intervals for the mean MOPs 1 and 2 values are in parentheses.

Figure 20. Experiment Four—Preliminary PEF Curves (Left Portion).

Figure 21 is a continuation of the curves in Figure 20 and explores the higher cost force options involving one or more LCSs. The space for attaining close to zero (≤ 0.5) leakers starts at one LCS for force options involving the LCSs; starts at two LCSs for force options without USVs; starts at three LCSs for force options without TUAVs; or with unarmed TUAVs. These different spaces are important to a commander who seeks to understand the impact of having only certain platform types and numbers available for a mission. A future study could employ a higher-resolution model to map the tradeoff curve of different mixes of LCSs, USVs, and TUAVs that can attain close to zero leakers.



Note: The 95% confidence intervals for the mean MOPs 1 and 2 values are in parentheses.

Figure 21. Experiment Four—Preliminary PEF Curves (Mid Portion).

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The four experiments provide useful insights into the influential factors and near Pareto efficient force configurations, based on the operational scenario, key assumptions, and within the limitations of the model. They outline the requirements for selecting the systems that will form an effective capability portfolio against swarming small boat attacks against a maritime force.

In selecting an energy-efficient and cost-effective capability portfolio to defend against, and reduce disruption to conventional missions facing, an unanticipated asymmetric threat's attack, this thesis shows that the number of LCSs, as part of a reconnaissance force ahead of the carrier group, is most critical in reducing the mean missile leakers, the mean boat leakers, the mean use of SAMs, and the mean cost of expended weapons. This is likely due to the number and range of the modified Hellfire missiles the LCSs carries, as compared to the Spike LR and APKWS weapons. The LCS also enables armed TUAV operations by carrying and deploying the TUAVs. In turn, adding LCSs increases the mean fuel consumed and the mean cost of added force.

Arming the TUAVs has a partial influence on reducing the use of SAMs, Hellfire missiles, Spike missiles, and the cost of expended weapons. This is mainly due to the APKWS being the cheapest missile used against the enemy boats. The number of TUAVs has similar effects but to a lesser extent.

The number of USVs is generally not influential in improving MOP results. This is likely due to the small number and short range of the Spike missiles the USV carries.

This thesis identifies possible energy-efficient and cost-effective force configurations the analysis of preliminary PEF curves with the number of missile and boat leakers plotted against fuel consumed and cost.

A minimum configuration for the reconnaissance force, specifically having at least three LCSs and five to six armed TUAVs, is needed to attain zero and close to zero (≤ 0.5) leakers, assuming the LCSs carry and deploy the TUAVs. Such a configuration

resulted from the LCS and armed TUAV being more influential on reducing leakers, as compared to the USV equipped with Spike missiles. This minimum force ensures that the naval force could continue unharmed on its conventional mission.

Imposing upper limits, from an efficiency perspective, on the reconnaissance force's diesel and aviation fuel consumption, as well as on costs of weapons expended and added force, reduces the maximum number of LCSs and TUAVs that could be deployed.

Mitigating policies, including operational and doctrinal ones, to defend successfully against conventional attacks from a small boat swarm involve selecting a "right-sized" mix of LCSs and armed TUAVs, that can provide effective force protection and, at the same time, limit fuel consumption, cost of weapons expended, and cost of added force.

Compared with the notional R&D options, increasing the number of LCSs and arming the TUAVs in the short term appear to be better investments for improving the carrier group's survival against a small boat swarm attack. The notional R&D options of increasing LCS Hellfire missile capacity, USV Spike missile capacity, TUAV APKWS missile capacity, and Spike missile range are not influential. Scaling autonomous USV technology to deploy up to 24 USVs from the current five has a moderate influence on reducing missile leakers.

The uncontrollable factors are observed to have minimal impact on missile and boat leakers, fuel and weapon consumption, and costs. This means that the capability options perform relatively robustly across a slew of different weapon hit probabilities, sensor range performances, and enemy boat numbers.

B. RECOMMENDATIONS

Based on the analyses from simulation model results in this thesis, a preliminary optimal force configuration would consist of three LCSs with five to six armed TUAVs, assuming the LCSs carry and deploy the TUAVs. This capability package would meet the mission requirements and fill the gaps identified during exploration of the decision space.

Further use of this research's insights can be made. Changes to MOP results can occur when there are different resources or platforms available, such as increasing or decreasing the number of LCSs and TUAVs, and/ or whether the TUAVs are armed.

Relevant MOP values can be aggregated into a single score as a more systematic method to select an optimum force configuration. In this method, there is flexibility to assign desired weights for each MOP according to stakeholder needs.

Other work can build on this research. New areas of study include:

1. Extend the modeling effort to incorporate both missile and gun exchanges. This will add fidelity to the measure of force protection effectiveness for the friendly forces. The modeling of gun attacks by friendly forces may result in fewer enemy boats launching C704 missiles or reaching the CVN.
2. Add complexity to the model such that C704s missiles target ships other than the CVN in the carrier group. This can lead to different results for the C704 leakers that reach the CVN.
3. Use alternate enemy behavior to examine the impact on force protection of both added and baseline forces; the enemy boats can choose to attack some LCSs or USVs before attacking the CVN. This can result in some LCSs or USVs being damaged.
4. Shore-based and air-launched ASCMs can be modeled to operate in concert with the enemy small boat ASCM attacks. This is a more stringent operational scenario to stress test the naval force's defenses.
5. A crossed design, e.g., the use of one design for controllable factors crossed with another design for uncontrollable factors, would make it easier to compare directly the performance of different capability portfolios. This research used only the NOB design across both controllable and uncontrollable factors.
6. Some neutral traffic can be added to the scenario to examine the impact of increased complexity in surveillance and targeting.
7. The cost of ships and platforms should be normalized to the same fiscal year to have a fairer comparison of costs between different force configurations.

C. SUMMARY

This research provides insights to decision makers on selecting an operational energy-efficient and cost-effective capability portfolio for the protection of a maritime force against a conventional small boat swarm attack. It identifies effective and feasible operational energy options to be part of the capability portfolio against small boat swarms. A wide variety of other model-based capability portfolio selection situations can employ the analysis methods used in this thesis.

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